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# ABSTRACTS

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## 9/27 Monday

| | | | |
|---|---|---|---|
| 7:30-9:00 | Registration and Continental Breakfast | | |
| | **Anasazi** | | **Sunset** |
| 9:00-11:30 | **Plenary Session** | | **Companions Meet and Greet** |
| | Welcome | | |
| 11:30-12:00 | Conference Photo | | |
| | **Anasazi North** | **Anasazi South** | **Sunset** |
| 13:30-15:30 | **Reaction Theory** | **Measurements of Cross Sections** | **Evaluated Libraries** |
| 15:30-17:30 | Poster A (**Zia**) and Coffee | | |
| 18:00-20:00 | Reception | | |

## 9/28 Tuesday

| | | | |
|---|---|---|---|
| 7:00-8:30 | Continental Breakfast | | |
| | **Anasazi North** | **Anasazi South** | **Sunset** |
| 8:30-10:10 | **Data Dissemination** | **Applications: Space** | **Measurements of Cross Sections** |
| 10:10-10:30 | Coffee | | |
| 10:30-12:10 | **Nuclear Data Evaluations** | **Fundamental Measurements** | **Measurements of Cross Sections** |
| 13:30-15:30 | **Application: Medicine** | **Measurements of Cross Sections** | **In Memory of S. Pearlstein** |
| 15:30-17:30 | Poster B (**Zia**) and Coffee | | |
| 18:00-19:30 | Concert | | |

## 9/29 Wednesday

| | | | |
|---|---|---|---|
| 7:00-8:30 | Continental Breakfast | | |
| | **Anasazi North** | **Anasazi South** | **Sunset** |
| 8:30-10:10 | **Application: Fuel Cycle, ADS** | **Astrophysics and Cosmology** | **Measurements and Facilities** |
| 10:10-10:30 | Coffee | | |
| 10:30-12:10 | **Nuclear Structure Evaluations** | **Measurements of Cross Sections** | **Astrophysics and Cosmology** |
| 13:30-15:10 | **Applications: Fusion** | **Measurements of Cross Sections** | **Nuclear Structure Evaluations** |
| 15:10-15:30 | Coffee | | |
| 15:30-17:30 | **Processing, Testing, and Validation of Evaluated Data** | **Standards** | **Nuclear Data Evaluations** |
| 18:30-21:30 | Poster C (**Zia**), Poster D (**Pavilion**), and Snacks | | |

## 9/30 Thursday

| | | | |
|---|---|---|---|
| 7:00-8:30 | Continental Breakfast | | |
| | **Anasazi North** | **Anasazi South** | **Sunset** |
| 8:30-10:10 | **Theory: Reaction Models** | **Measurements: Facilities** | **Applications: Fission Energy** |
| 10:10-10:30 | Coffee | | |
| 10:30-12:30 | **Theory: Reaction Models** | **In Memory of S. Raman** | **Applications: Fission Energy** |
| 13:50-15:20 | **Processing, Testing, and Validation of Evaluated Data** | **Applications: Safety** | **Theory: Off Stability** |
| 15:20-15:40 | Coffee | | |
| 15:40-17:30 | **Evaluation Techniques** | **Application: Non-Proliferation** | **Nuclear Theory: Advances in Calculational Methods** |
| 19:00-22:00 | Banquet | | |

## 10/1 Friday

| | | | |
|---|---|---|---|
| 7:00-8:30 | Continental Breakfast | | |
| | **Anasazi North** | **Anasazi South** | **Sunset** |
| 8:30-10:10 | **Theory and Evaluation** | **Measurements and Experimental Techniques** | **Uncertainty Quantification** |
| 10:10-10:30 | Coffee | | |
| 10:30-11:30 | **Plenary Session (Anasazi)** | | |
| 11:30-12:15 | **Closeout – Plenary** | | |

# Plenary Session

**Anasazi**, Monday 9:00–11:30

[505] Developments in Nuclear Energy Technologies and Nuclear Data Needs
**P.J. Finck**

[547] Particle physics with cold neutrons
**D. Dubbers**

## [505] Developments in Nuclear Energy Technologies and Nuclear Data Needs

Phillip J. Finck[1], Hussein S. Khalil[1], Massimo Salvatores[2]

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The objective of this paper is to identify nuclear systems and technologies currently under development, along with the nuclear data challenges these technologies will raise. The US R&D programs are taken as an example to support our general conclusions.

The nuclear industry has two immediate objectives: run existing plants more efficiently, and where appropriate extend their licenses. In general, current computational methodologies are adequate for these applications, and there is no urgent need for new or improved nuclear data.

A more ambitious objective for current plants might be the increase of the average fuel discharge burnup, maybe up to 100,000MWd/mt. This would require that fuel enrichment be increased beyond the current 5% limit. While new cross sections would probably not be needed, it might become necessary to validate and increase the accuracy of existing data for these new applications. This will involve criticality safety issues and possibly the need to better determine the composition of spent fuel.

Future reactors, such as ALWR's, will first be extrapolations of current design and as long as they are used in a once through mode, will not require new data.

The following generation of reactors, such as the cogeneration Very High Temperature Reactor (VHTR) needs to be seriously reviewed as far as nuclear data and computational methods are concerned: it is not at all clear that the current *ad hoc* approach will be sufficiently rigorous for guaranteeing computational results of very high quality and to minimize margins for design.

Other reactor types, like GCFRs, can introduce the need for improved data related to new materials (e.g. fuel matrices, reflectors etc.)

The most demanding challenges will occur in the following phase, when closure of the fuel cycle occurs, either in thermal or fast reactors, and potentially making use of accelerator driven systems. The paper will first describe the technical and institutional elements that will guide the development and implementation of these technologies. The paper will then summarize for each of these technologies, the major technical uncertainties that need to be solved, including the need for a better formalized nuclear data file with associated covariance matrices.

In general, data needs for the full fuel cycle assessment will play a major role to define guidelines for future requirements in the nuclear data field.

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## [547] Particle physics with cold neutrons

Dirk Dubbers

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Cold and ultracold neutrons are used in a larger number of experiments to explore current problems from the fields of particle physics and cosmology. An overview is given on the questions addressed, the experiments running, and the future projects in this field.

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# Reaction Theory

**Anasazi North**, Monday 13:30–15:30

[518] Recent Microscopic Calculations Applied to Nuclear Fission : Fission Barriers and Fission Fragment Distributions
**H. Goutte [Invited]**

[127] Nucleon-Nucleus Scattering and Dirac Phenomenology: What We Have Learned and What Remains
**B.C. Clark [Invited]**

[121] Nuclear ground-State Observables from Relativistic Mean-Field Models: Masses, Densities, Radii, Single-Particle Levels
**T.J. Buervenich**

[447] Theoretical Evaluation of Actinide Fission and Capture Cross Sections
**J.E. Lynn**

[151] Calculations of Fission Properties Using Microscopic Models for Astrophysics Applications
**P. Demetriou**

# Measurements of Cross Sections

**Anasazi South**, Monday 13:30–15:30

[362] Measurement of the $^{90,91,92,94,96}$Zr(n,$\gamma$) Cross-Sections at n_TOF
**C.R. Moreau**

[338] Cross Section Measurements for (n,xn) Reactions by In-Beam Gamma-ray Spectroscopy
**A. Pavlik**

[427] Cross sections for $\gamma$-ray Production in the $^{191}$Ir$(n, xn\gamma)$ Reactions
**N. Fotiades**

[162] A Nuclear Data Project in Japan
**M. Igashira**

[ 3] Measurement of Residual Nuclueus Cross Sections and Recoil Energies in p + Fe
**C. Villagrasa**

[549] Measurement of Continuous-Energy Neutron-Incident Neutron-Production Cross Section
**N. Shigyo**

# Evaluated Libraries

**Sunset**, Monday 13:30–15:30

[484] Status of the JENDL Project
**K. Shibata [Invited]**

[420] Recent Advances in the ENDF/B Library
**P. Oblozinsky [Invited]**

[523] Status of the JEFF nuclear data library
**A. Nouri [Invited]**

[524] BROND
**A. Ignatyuk [Invited]**

## [518] Recent microscopic calculations applied to nuclear fission : fission barriers and fission fragment distributions

H. Goutte

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Among the different theoretical approaches able to describe the fission process, microscopic ab initio ones have the advantage of being capable of making reliable predictions even in nuclei where few or no data is known. The main interest of this kind of approach is to describe both statical and dynamical aspects of fission as well as the internal and collective properties of the fissioning system in a consistent manner. Due to the complexity of the formalism and comparatively large computational times, extensive sets of results suitable for large scale data evaluations will not be available till a few years. Nevertheless, as I will show, a lot of progress has been made recently in order to derive fragment properties taking into account the full dynamics of the fission process in a consistent microscopic time-dependent approach, and very promising results have been obtained.

In this talk, I will present an overview of recent microscopic approaches to nuclear fission including a review of the major developments in the field. Recent results about fission barriers and fragment mass, charge and kinetic energy distributions in low-energy actinide fission will be shown and discussed.

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## [127] Nucleon-Nucleus Scattering and Dirac Phenomenology: What We Have Learned and What Remains

Bunny C. Clark[1], Lisa K. Kerr[1], Shinichi Hama [2]

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A new method for extracting neutron densities from intermediate energy elastic proton-nucleus scattering observables uses a global Dirac phenomenological (DP) approach which is based on the Relativistic Impulse Approximation (RIA). This analysis provides energy independent values for the RMS neutron radius, $R_n$ and the neutron skin thickness, $S_n$, in contrast to the energy dependent values obtained by previous studies. The vector point proton density distribution, $\rho_v^p$, is determined from the empirical charge density after unfolding the proton form factor. The other densities, $\rho_v^n$, $\rho_s^p$, $\rho_s^n$, are parametrized. We have obtained values of $S_n$ and $R_n$ for $^{40}$Ca, $^{48}$Ca, $^{208}$Pb and other targets which agree with nonrelativistic Skyrme models and relativistic Hartree-Bogoliubov model extended to include density dependent meson-nucleon couplings. Our results are generally not in agreement with relativistic mean-field models. We have found that substantial progress in extracting the neutron densities from proton-nucleus elastic scattering is made by using a global approach focusing on the energy region where the RIA is capable of reproducing experiment well.

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## [121] Nuclear ground-state observables from relativistic mean-field models: masses, densities, radii, single-particle levels

Thomas J. Buervenich, David G. Madland

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We report on the current status of relativistic mean-field models for the calculation and prediction of nuclear ground-state observables. These models are quite powerful and can be applied to light (A $\geq$ 16), medium, and heavy nuclei (spherical and deformed) and allow realistic extrapolations to the drip lines and to superheavy nuclei. From a single calculation one obtains a plethora of microscopic information about the chosen nucleus. We discuss several of the corresponding observables that are then simultaneously calculated as well as the accuracy with which they can be determined within the current models. Finally, we discuss recent model enhancements, connections to more fundamental physics, and future work.

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## [447] Theoretical Evaluation of Actinide Fission and Capture Cross Sections

J. Eric Lynn

*Los Alamos National Laboratory and Sumner Associates*

Requirements for data on fission and capture cross-sections of the shorter-lived actinides have become of increasing importance recently, with needs arising from fields such as nuclear non-proliferation, nuclear criticality safety, nuclear waste transmutation and nuclear astrophysics. Many of the nuclides of interest have such short half-lives that it is very difficult to obtain adequate direct experimental data on their neutron cross-sections. For some of them some very limited neutron cross-section data are available. For others, data from reactions such as (t,pf) give valuable information on aspects of the compound nucleus such as fission barrier parameters that can be used in calculations of the neutron cross-sections. In this paper we survey the theory and methods for calculating neutron cross-sections of the actinides of most practical interest up to a few MeV. We show how direct and indirect experimental data can be exploited to determine model parameters for the calculations and we present recommended values for barrier heights, level densities and other parameters required by the theory.

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## [151] Calculations of fission properties using microscopic models for astrophysics applications

Paraskevi Demetriou, Matthieu Samyn, Stephane Goriely

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Nuclear fission could play a crucial role in the r-process nucleosynthesis under certain hydrodynamical conditions. If under these conditions the nucleosynthesis reaches the transuranium region, then fission will prohibit the synthesis of the superheavy elements. Neutron-induced and beta-delayed fission in particular, in astrophysical environments where the neutron densities are sufficiently large to produce fissile nuclei may strongly influence the abundances in the lower mass region through the re-cycling of the r-process material, while spontaneous fission will affect the final abundance pattern, especially the production of long-lived radiocosmochronometers Th and U. Of course all of these fission processes involve extremely neutron-rich nuclei that are unable to be measured in the laboratory. It is therefore of paramount importance to make reliable predictions of the relevant beta-delayed and neutron-induced fission rates, as well as the spontaneous fission half-lives, of all these unknown nuclides, starting from relatively close to the stability line and going out towards the drip line. In this respect, an attempt has been made to treat all aspects of fission on a microscopic basis, using a Skyrme-Hartree-Fock approach for the calculation of masses, fission barriers and fission level densities.

We present the results of the analysis of the potential energy surfaces obtained with a Skyrme-Hartree-Fock-Bogoliubov method in a multidimensional deformation space. Both *static* and *dynamic* fission paths are calculated and the corresponding spontaneous fission half-lives are compared with experimental data. The barrier heights and widths along the *static* paths are also used to calculate the fission transmission coefficients within the Hill-Wheeler theory. The latter are then used to obtain neutron-induced fission cross sections within the framework of the Hauser-Feshbach theory. Corrections for subbarrier effects are taken into account. Apart from the fission barriers, nuclear level densities at ground-state and saddle-point deformations are also important quantities in the calculations of neutron-induced fission cross sections. In our approach they are obtained from microscopic statistical calculations based on a constrained Skyrme-Hartree-Fock description of the nucleus. The results of our calculations are first compared with existing experimental data in the actinide region. Several improvements, in particular on the nuclear level densities are discussed. Finally, large-scale calculations of fission haf-lives and neutron-induced fission cross sections, as well as the impact on r-process nucleosynthesis, are presented.

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## [362] Measurement of the $^{90,91,92,94,96}$Zr(n,$\gamma$) cross-sections at n_TOF

Christophe R. Moreau

*INFN, Trieste and the n_TOF collaboration*

The (n,$\gamma$) cross-sections for the stable Zr isotopes have important implications in nuclear technologies as well as for studies in the field of nuclear astrophysics. In particular the NEA "High Priority Nuclear Data Request List" [1] ask for a fine cross-section determination for (n,$\gamma$) reactions from thermal to 1 MeV neutron energy.

The innovative features of the n_TOF CERN facility, and in particular the very high instantaneous neutron flux [2], the high resolution and the low background results in the possibility to obtain a very good signal-to-background ratio for such measurements, thus allowing for an accurate determination of the relatively low capture cross-section for these isotopes. In particular the goal of these measurements is to improve the definition of cross-sections and resonances parameters, reducing the uncertainties of a factor three, with respect to the previous available experimental data.

After the description of the experimental apparatus, based on C6D6 detectors, we will present a detailed discussion of the data analysis, which is based on the Pulse Height Weighting Technique. A careful analysis of the different background components has been performed by means of suitable measurements with Pb samples, as well as with black-resonance filters. After the determination of the capture yield, accurate cross-sections for the stable Zr(n,$\gamma$) reactions are then extracted. The results on the analysis in the resonance region are presented together with the cross-section for the unresolved resonance region. A discussion on the estimated magnitude of the systematic uncertainties will be presented.

References
[1] "The NEA High priority Nuclear Data Request List", Status in May 1998, OECD-NEA Nuclear Science Committee.
[2] Proposal for a Neutron Time of flight Facility, CERN-SPSC 99-8, SPSC/P 310, 17 March 1999.
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## [338] Cross section measurements for (n,xn) reactions by in-beam gamma-ray spectroscopy

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New concepts as fast reactors and accelerator driven systems (ADS) for waste incineration or energy production cause a demand for neutron cross section data over a wide energy range. Precise (n,xn) cross sections are required as these reactions contribute significantly to the neutron balance and the modification of the neutron spectrum. The present existing data base for (n,xn) reactions is scarce, especially for x>2, as previous nuclear data measurement programs had often their emphasis on a neutron energy range below their reaction thresholds. Existing experimental data and also evaluated data on (n,xn) reactions often show large discrepancies. Thus in the frame of the n_TOF project a program to measure (n,xn) cross sections was initiated.

One method to investigate (n,xn) reactions is the detection of promptly emitted gamma-rays in low-lying transitions in the residual nucleus by high-resolution gamma-ray detectors. Using the time-of-flight method to determine the incident neutron energy, this method can also be used at "white" neutron beams. The measured quantities, however, are production cross-sections for strong gamma-ray transitions in the residual nucleus, which have to be combined with nuclear model calculations to give total (n,xn) cross sections. Thus in a combination of measured gamma-ray production cross sections (which contribute in some cases up to 80%-90% to the total (n,xn) cross section) and model calculations cross sections for (n,xn) reactions can be determined where the activation method is not possible, either due to the residual nucleus properties or the lack of monoenergetic neutron sources.

We have studied the possibilities of performing gamma-ray emission measurements on $^{232}$Th at the quasi-monoenergetic neutron source of the Cyclotron Research Center in Louvain-la-Neuve, Belgium and on Pb at the GELINA white neutron beam at the Institute for Reference Materials and Measurements in Geel, Belgium. Prompt gamma-ray spectra were recorded using high-purity germanium detectors. To obtain a good compromise between energy resolution and dead time at the GELINA neutron beam, we developed a data acquisition system based on fast flash ADCs and used digital pulse processing techniques. Gamma lines corresponding to low-lying transitions in residual nuclei of different (n,xn) reactions were clearly identified and analyzed in several test measurements at both facilities. Preliminary excitation curves for the production of prompt gamma-rays in $^{206,207,208}$Pb in a natural lead sample

show good agreement with predictions based on nuclear model calculations. After these successful tests measurements to obtain $^{232}$Th(n,5n) and $^{207}$Pb(n,xn) cross sections (the latter ones with an isotopically enriched sample) are planned to be performed in the first half of 2004 in Louvain-la-Neuve and Geel, respectively. Also the feasibility of a measurement with a very active sample like $^{233}$U at n_TOF (CERN) is now being considered. Additional tests at this facility will be performed early in 2004.

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## [427] Cross sections for $\gamma$-ray production in the $^{191}$Ir$(n, xn\gamma)$ reactions

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Discrete $\gamma$-ray spectra have been measured for nuclei populated in $^{191}$Ir$(n, xn\gamma)$ reactions, with $x \leq 7$, as a function of incident neutron energy using neutrons from the "white" neutron source at the Los Alamos Neutron Science Center's WNR facility. The energy of the neutrons was determined using the time-of-flight technique. The data were taken using the GEANIE spectrometer comprised of 26 high-purity Ge detectors with 20 BGO escape-suppression shields. The cross sections for emission of several $\gamma$-rays of $^{185-191}$Ir were determined for neutron energies 1 MeV $< E_n <$100 MeV and a comparison with model calculations, using the GNASH reaction model, was made. These cross sections are also compared with older GEANIE results from the similar $^{193}$Ir$(n, xn\gamma)$ reactions.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Los Alamos National Laboratory under contract No. W-7405-ENG-36 and Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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## [162] A Nuclear Data Project in Japan

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The neutron capture and fission cross sections of minor actinides are very important for the R&D of innovative nuclear reactors. The present status of those cross section data is, however, quite poor both in quality and in quantity. Thus, we proposed a project entitled "Fundamental R&D on Neutron Cross Sections for Innovative Reactors using Advanced Radiation Measurement Technology" to the Ministry of Education, Culture, Sports, Science and Technology and it was approved as one of "Innovative Nuclear Energy System Technology Development Projects".

This project consists of three R&D items: (1) the development of advanced measurement technology, (2) the acquirement of neutron cross sections of minor actinides, and (3) the development of neutron cross section utilization system. This project started in 2002 and will continue until 2007. The total budget is 757 million yen.

In the development of advanced measurement technology, we will construct a $4\pi$ Ge spectrometer consisting HPGe crystals and BGO shields for capture cross section measurement. The design study of

the spectrometer has been performed by Monte-Carlo simulation. New fission chambers are also being developed for fission cross section measurement.

The measurement for minor actinides such as Am-241 and Am-243 will be performed from 2005 to 2007, using existing neutron sources in Japan. The preparation of neutron beam lines, neutron monitor detectors, and minor actinide samples is in progress.

In the development of neutron cross section utilization system, we will construct the utilization system and re-evaluate the neutron cross sections of minor actinides on the basis of the experimental data obtained in this project. The functions of utilization system are being designed. The system will provide convenient portal sites for nuclear data users.

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## [3] Measurement of residual nuclueus cross sections and recoil energies in p + Fe

Carmen VILLAGRASA[1], Alain BOUDARD[1], Jean-Eric DUCRET[1], Beatriz FERNANDEZ[1], Sylvie LERAY[1], Claude VOLANT[1], Wojtech WLAZŁO[1], Peter ARMBRUSTER[2], Timo ENQVIST[2], Fairouz HAMMACHE[2], Kerttuli HELARIUTTA[2], Beatriz JURADO[2], Maria-Valentina RICCIARDI[2], Kerl-Heinz SCHMIDT[2], Klaus SÜMMERER[2], Florence VIVÉS[2], Orlin YORDANOV[2], Laurent AUDOUIN[3], Laure FERRAN[3], Fanny REJMUND[3], Claude STÉPHAN[3], Laurent TASSAN-GOT[3], Jose BENLLIURE[4], Enrique CASAREJOS[4], Manuel FERNANDEZ[4], Jorge PEREIRA[4], Serge CZÁJKOWSKI[5], D. KARAMANIS[5], Michel PRAVIKOFF[5], Jeff GEORGE[6], R. A. MEWALDT[6], Nathan YANASAK[6], Mark WIEDENBECK[7], Jim CONNEL[8], T. FAESTERMANN[9], Andreas HEINZ[10], Arnd JUNGHANS[11]

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The production of residual nuclei in p + Fe collisions has been measured at GSI on the FRS facility by mean of the reverse kinematic techniques at 300 MeV/A, 500 MeV/A, 750 MeV/A, 1 GeV/A and 1.5 GeV/A. A consistent set of cross sections for all isotopes produced above 0.01 mb is obtained and will be presented. The experiment gives also access to the momentum spectra of each isotope, so that properly transformed, the recoil energy of residues is experimentally known in the usual kinematics (proton on iron).

These data are interesting at several levels. Originally triggered by astrophysical considerations, they provide a detailed experimental knowledge of the spallation process around energies frequently found in cosmic radiations, and for elements of special importance in the nucleosynthesis and in the interstellar medium.

For hybrid systems, the proton beam accelerated under vacuum will have to cross a window before entering the spallation target and the subcritical reactor. Whether or not this window is considered as a safety barrier is a matter of debates heavily function of the window resistance. In most of the designs, this thin window is dominantly made of iron, so that the data obtained here are directly useful (with no transport corrections) to know the amount of impurities accumulated and the damage due to the recoil of residual nuclei.

As a test of spallation models, iron data complements the previous results obtained on heavy nucleus (U, Pb and Au) by a large step on the target mass. An effective beam energy dependence is also obtained for the first time in this type of experiments. The comparison with various combinations of intra-nuclear cascades and evaporations will be presented and discussed.

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## [549] Measurement of Continuous-Energy Neutron-Incident Neutron-Production Cross Section

Nobuhiro Shigyo[1], Satoshi Kunieda[1], Takehito Watanabe[1], Shusaku Noda[1], Kenji Ishibashi[1], Yosuke Iwamoto[2], Daiki Satoh[2], Takashi Nakamura[3], Robert C. Haight[4]

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Intermediate-energy proton accelerators are applicable to facilities such as accelerator-driven subcritical systems, which have aroused a great deal of interest in cross sections in this intermediate-energy region. For design of facilities, proton-incident double-differential cross sections (DDX) have been measured. These data contributed to improvement of calculation codes. Proton-incident data, however, give limited information on the reaction. At the intermediate energies, protons induce the cascade reaction dominantly starting from the initial p-n collision for heavy neutron-rich targets. Neutron-incident DDX data will play an important role in quantitatively understanding the whole cascade process. Neutron-incident data, however, have not been obtained above 100 MeV at all.

It is well known that the optical potential changes significantly around 100 MeV. Proton-incident data cover this region to some extent. It is necessary for the neutron-incident DDX data also to cover the nuclear-potential changing region. Neutron-incident data will give information complementary to proton-incident data with regard to intra-nuclear cascade codes and the optical potential.

The experiment was performed at the Weapons Neutron Research (WNR) facility of Los Alamos Neutron Science Center. The flight time of the emitted neutron was not obtained directly. To avoid this difficulty, the energy of emitted neutron was obtained by the energy deposition in a detector. The incident neutron energy was gotten by the time-of-flight method between the accelerator and the emitted neutron detector. Two types of detectors were adopted to measure a wide energy range of neutrons. Liquid organic scintillators covered emitted neutron energies up to 100 MeV. Recoil proton detectors, which consist of recoil proton radiators and phoswich-type NaI(Tl) scintillators, were used for neutrons above several tens MeV into the several hundred MeV range. Iron and lead were used as sample materials. The experimental data were compared with the evaluated nuclear data and with the results of GNASH and PHITS codes. The details of experiment will be presented at the poster session.

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## [484] Status of the JENDL Project

K. Shibata, T. Nakagawa, T. Fukahori, O. Iwamoto, N. Otsuka, J. Katakura

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General Purpose File

JENDL-4 is being developed for researches on innovative reactors, high burn-up and the use of MOX fuels for LWR, criticality safety considering burn-up credit, therapy, astrophysics, and so on. The library will include charged-particle and photon induced reaction data as well as spontaneous fission data for a limited number of nuclei in addition to neutron induced reaction data. The maximum incident energy can be extended to higher values than 20 MeV depending on data needs. Key subjects are as follows: extension of incident particles and energies, to solve problems with JENDL-3.3, improvement of minor actinide and FP data, and evaluations of covariances, fission product yields, gamma-ray production data and charged-particle spectra. Quality assurance is regarded as important for JENDL-4. The Japanese Nuclear Data Committee (JNDC) is responsible for production of reactor constants for typical applications such as continuous-energy Monte Carlo and multi-group transport calculations and burn-up calculations.

Special Purpose Files

Part of the JENDL High Energy Files will be released this year: the neutron- and proton-induced reaction data with top priority up to 3 GeV and photo nuclear reaction data. Evaluation of lower priority data continue. For the development of ADS, the Actinide File is being made to improve the accuracy of minor actinide data in JENDL-3.3. Furthermore, covariance data for some nuclei are also evaluated for ADS.

Developments of Codes and Data Utilization System

Optical and statistical model codes are developed in order to reflect recent advances in nuclear theory on data evaluations. For users' convenience, we are working on the development of the data utilization

system consisting of retrieval, visualization, processing and dissemination. The system will be available on internet, and standard criticality and shielding benchmark tests can be performed in an easy way. The system will provide a convenient portal site for nuclear data users.

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## [420] Recent Advances in the ENDF/B Library

Pavel Oblozinsky

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Overview of recent advances in the US evaluated nuclear reaction data library, ENDF/B, as embodied in current and forthcoming releases is given. The Cross Section Evaluation Working Group (CSEWG) that maintains the library issued it latest version, ENDF/B-VI release 8, in October 2001.

The current effort of the CSEWG is focusing on the development of a new version of the library, ENDF/B-VII, scheduled for release in December 2005. Among its entirely new features is inclusion of 160 photonuclear evaluations. Majority of new and improved evaluations, in particular in the actinide region, comes from LANL. Contributions from ORNL focus on neutron resonance data, while BNL leads effort to improve evaluations for fission products. Strong emphasize is given to data validation process.

We will attempt to convey the excitement of new advances in the database, as grounded in recent experiments or model calculations, and also discuss the users of the database and the applications that are motivating the work.

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## [523] Status of the JEFF nuclear data library

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[2] *CEA Cadarache*
[3] *UKAEA Culham*
[4] *CEA Bruyeres-le-Chatel*
[5] *JRC-IRMM Geel*
[6] *NEA Data Bank*

The status of the Joint Evaluated Fission and Fusion file (JEFF) is described. The next version of the library, JEFF-3.1, comprises a significant update of actinide evaluations, evaluations emerging from European nuclear data projects, the activation library JEFF-3/A, the decay data and fission yield library, and fusion-related data files from the EFF project. In particular, there are substantial revisions in the following cross section evaluations: U-238, Pu-240, Am-241, Cr-52, Rh-103, I-129, Bi-209, Ca, Sc, Ti, Fe, Ge and Pb isotopes. These revisions were motivated by the availability of new measurements, modelling capabilities, or trends from integral experiments. Various pre-release validation efforts are underway, mainly for criticality and shielding of thermal and fast systems. This JEFF-3.1 library is expected to provide improved performances with respect to JEF-2.2 for a variety of scientific and industrial applications.

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## [524] BROND

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# Data Dissemination

**Anasazi North**, Tuesday 8:30–10:10

[525] Panel Discussion / Data Dissemination and International Collaborations
**[Invited Panel] T. Fukahori, A. Ignatyuk, F. Kondev, K.-L. Kratz, V. McLane, A. Nichols, A. Nouri, O. Schwerer, A. Sonzogni [Chair], D. Winchell**

# Applications: Space

**Anasazi South**, Tuesday 8:30–10:10

[495] Physics Models in the MARS15 Code for Accelerator and Space Applications
**N.V. Mokhov [Invited]**

[462] Propagation of cosmic rays in the Galaxy
**I.V. Moskalenko [Invited]**

[112] Experimental Double-Differential Light-Ion Production Cross Sections for Silicon at 95 MeV Neutrons
**U. Tippawan**

[149] Cross Section Measurements for Proton- and Neutron- Induced Reactions to Understand Cosmic Ray Interactions on Earth and in Space
**J.M. Sisterson**

# Measurements of Cross Sections

**Sunset**, Tuesday 8:30–10:10

[402] Determination of Thermal Neutron Capture Cross Sections Using Cold Neutron Beams
**T. Belgya**

[360] Potential of AMS for Quantifying Long-Lived Reaction Products
**A. Wallner**

[157] Measurements of Total Cross Sections at Pohang Neutron Facility
**G. Kim**

[ 23] Nuclear Level Densities of $^{56}$Co, $^{57}$Co, $^{90}$Nb, $^{94}$Nb from Neutron Evaporation Spectra
**B.V. Zhuravlev**

[489] Search for Subthreshold Neutron Production in Be
**R.E. Chrien**

## [525] Data Dissemination and International Collaborations

Alejandro Sonzogni[1], Tokio Fukahori[2], Anatoly Ignatyuk[3], Filip Kondev[4], Kerl-Ludwig Kratz[5], Vicki McLane[1], Alan Nichols[6], Ali Nouri[7], Otto Schwerer[6], David Winchell[1]

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[2] *JAERI, Nuclear Data Center, Japan*
[3] *IPPE, Obninsk, Russia*
[4] *ANL, USA*
[5] *Istitut für Kernchemie, Universität Mainz, Germany*
[6] *IAEA, Nuclear Data Section, Austria*
[7] *OECD, Nuclear Energy Agancy, France*

This session will be a panel discussion on data dissemination (web sites and publications, nuclear astrophysics data) and international collaborations (NSDD, NRDC and WPEC). About ten panelists will gather to discuss current issues and future directions. Present challenges and exciting new developments will be presented.

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## [495] Physics Models in the MARS15 Code for Accelerator and Space Applications

N. V. Mokhov[1], K. K. Gudima[2], S. G. Mashnik[3], I. L. Rakhno[4], A. J. Sierk[3], S. I. Striganov[1]

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The MARS code system, developed over 30 years, is a set of Monte Carlo programs for detailed simulation of hadronic and electromagnetic cascades in an arbitrary geometry of accelerator, detector and spacecraft components with particle energy ranging from a fraction of an electron volt up to 100 TeV. The status, major developments and new features of the MARS15 (2004) version are described in this paper with an emphasis on modeling physics processes. This includes an extended list of elementary particles and arbitrary heavy ions, their interaction cross-sections, inclusive and exclusive nuclear event generators, photo-hadron and photo-muon production, correlated ionization energy loss and multiple Coulomb scattering of single-charged particles and heavy ions, bremsstrahlung and direct pair production. In particular, the details of enhanced systematics of elementary particle and heavy-ion nuclear cross-sections, a new model for leading baryon production and implementation of advanced versions of the Cascade-Exciton Model (CEM2003), and the Quark-Gluon String Model (LAQGSM03) are given. The applications that are motivating these developments, needs for better nuclear data, and future physics improvements are described.

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## [462] Propagation of cosmic rays in the Galaxy

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Studies and discoveries in cosmic-ray physics and generally in Astrophysics provide a fertile ground for research in many areas of Particle Physics and Cosmology, such as the search for dark matter, antimatter, new particles, and exotic physics, studies of the nucleosynthesis, origin of Galactic and extragalactic gamma-ray diffuse emission, formation of the large scale structure of the universe etc. In several years new missions are planned for cosmic-ray experiments, which will tremendously increase the quality and accuracy of cosmic-ray data. On the other hand, direct measurements of cosmic rays are possible in only one location on the outskirts of the Milky Way and present only a snapshot of very dynamic processes. It

has been recently realized that direct information about the fluxes and spectra of cosmic rays in distant locations is provided by the Galactic diffuse gamma-rays, therefore, complementing the local cosmic-ray studies. A wealth of information is also contained in the isotopic abundances of cosmic rays, therefore, accurate evaluation of the isotopic production cross sections is of primary importance for Astrophysics of cosmic rays, studies of the galactic chemical evolution, and Cosmology. In this talk, we will show new results obtained with GALPROP, the most advanced numerical model for cosmic-ray propagation, which includes in a self-consistent way all cosmic-ray species (stable and long-lived radioactive isotopes from H to Ni, antiprotons, positrons and electrons, gamma rays and synchrotron radiation), and all relevant processes and reactions.

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## [112] Experimental Double-Differential Light-Ion Production Cross Sections for Silicon at 95 MeV Neutrons

Udomrat Tippawan[1], Stephan Pomp[1], Ayse Atac[1], Bel Bergenwall[1], Jan Blomgren[1], Angelica Hildebrand[1], Cecilia Johansson[1], Joakim Klug[1], Philippe Mermod[1], Michael Österlund[1], Klas Elmgren[2], Nils Olsson[2], Olle Jonsson[3], Alexander Prokofiev[3], Leif Nilsson[1], Pawel Nadel-Turonski[4], Somsak Dangtip[5], Valentin Corcalciuc[6], Yukinobu Watanabe[7], Arjan Koning[8]

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The radiation effects induced by terrestrial cosmic rays in microelectronics, on board aircrafts as well as at sea level, have recently attracted much attention. The most important particle radiation is due to spallation neutrons, created in the atmosphere by cosmic-ray protons. When, e.g., an electronic memory circuit is exposed to neutron radiation, charged particles can be produced in a nuclear reaction. The charge released by ionization can cause a flip of the memory content in a bit, which is called a single-event upset (SEU). This induces no hardware damage to the circuit, but unwanted re-programming of memories, CPUs, etc., can have consequences for the reliability, and ultimately also for the safety of the system.

Data on energy and angular distribution of the secondary particles produced from neutron-silicon nuclei are essential input for analyses and calculation of SEU rate. In this work, double-differential cross sections of inclusive light-ion (p, d, t, $^3$He and $\alpha$) production in silicon, induced by 95 MeV neutrons, are presented. Angular distributions are measured at eight laboratory angles from 20° to 160° in steps of 20°. Deduced energy-differential, angle-differential and total cross sections are reported as well. Experimental cross sections are compared to theoretical reaction model calculations and existing experimental data in the literature.

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## [149] Cross section measurements for proton- and neutron- induced reactions to understand cosmic ray interactions on earth and in space

Janet M. Sisterson

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Primary cosmic rays interact directly with the extraterrestrial bodies and cosmic ray shower particles interact with the earth's surface to produce small quantities of radionuclides and stable isotopes, which can be measured routinely using appropriate techniques. Theoretical models are used to analyze these measurements to learn the history of the object or the cosmic rays that fell upon it and cross sections for reactions producing these cosmogenic nuclides are essential input to these models. Most primary cosmic rays are protons and good measurements of the cross sections for proton-induced reactions are the first need. Most relevant cross sections are now well measured but discrepancies still exist between the

measurements and calculations. One possible explanation is that neutrons produced in primary cosmic ray interactions also initiate spallation reactions contributing significantly to the cosmogenic nuclide inventory. Few of the relevant cross sections for these neutron-induced reactions have been measured at energies >30 MeV.

A systematic study is in progress to measure as many of these needed cross sections for neutron-induced reactions as possible, using two different techniques. Cross sections at selected unique neutron energies >70 MeV are measured at iThemba LABS, South Africa (iTL) using quasi-monoenergetic neutron beams. 'Average' cross sections are measured at the Los Alamos Neutron Science Center (LANSCE), using 'white' neutron beams with an energy range of $\sim$ 0.1 - 750 MeV. To date, many cross sections for the production of relevant relatively short-lived radionuclides have been measured using non-destructive gamma-ray spectroscopy. These 'average' cross sections plus the measurements made at iTL for high neutron energies and any existing measurements (in nearly all cased for energies <30 MeV) can be combined to derive excitation functions to use as input to the theoretical model calculations.

The cross section measurements that have been completed to date and their importance in understanding cosmic ray interactions will be presented.

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## [402] Determination of thermal neutron capture cross sections using cold neutron beams

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Neutron cross sections of the components of nuclear fuels, long-lived nuclear waste and structural materials used in reactor and accelerator based nuclear energy production and transmutation systems are of special significance. The thermal cross section is an important normalization point used in the processing and evaluation of neutron resonance data. Its accurate value is sometimes difficult to determine by integral measurements, such as by the neutron activation method, due to the improper knowledge of the neutron energy distribution and the inaccuracy of radioactive decay data.

Intense guided beams of cold neutrons provide the means to determine accurately the cross section for capture (and fission) at the thermal energy, without the disturbing effect of resonances. For capture, the cross section can be inferred from the partial production cross sections of the primary or ground-state transitions measured relative to an internal standard, or from the beta decay lines. Using a beam chopper and a digital analyzer enable accurate activation measurements of ground state and isomer cross sections on very short-lived reaction products.

The capabilities of the new method developed at the Budapest cold neutron facility are demonstrated by recent results for the fuel element constituent $^{238}$U and for the most important long-lived fission products, $^{99}$Tc and $^{129}$I.

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## [360] Potential of AMS for quantifying long-lived reaction products

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Accelerator mass spectrometry (AMS) represents a powerful technique for the detection of long-lived radionuclides through ultra-low isotope ratio measurements. In many cases, counting atoms rather than measuring decay products yields much higher sensitivities. The potential of AMS will be demonstrated on typical radionuclides of interest with half-lives between some tens of years up to hundred million years.

A variety of nuclides are produced both in nature (e.g. cosmogenic) as well as in man-made fission and fusion devices. Particularly long-lived radionuclides may lead to significant long-term waste disposals. In addition, long-lived radionuclides can also serve as diagnostic tools for different applications. For such nuclides, production cross-sections as well as total induced activities are key parameters. Therefore, well-established data on their production rates are highly desired.

The Vienna Environmental Research Accelerator (VERA) represents a state-of-the-art AMS facility which provides the ability for quantifying nuclides over the whole mass range. Some of the routinely measured radioisotopes are e.g. $^{10}$Be, $^{14}$C, $^{26}$Al, $^{129}$I, $^{182}$Hf, $^{236}$U and $^{244}$Pu . Another example, complementing the VERA lab, are AMS facilities which provide high particle energies. For example, the AMS setup at the Accelerator laboratory in Munich, which comprises a 14-MV tandem accelerator in combination with a gas-filled-magnet system. This combination offers the best suppression of isobaric

background, in particular in the medium mass range: Isotopes like $^{63}$Ni, $^{53}$Mn, $^{59}$Ni, $^{41}$Ca, $^{60}$Fe are routinley measured in a wide range of applications.

Lack of information exists for a list of nuclides as pointed out by nuclear data requests. The potential of AMS will be demonstrated by means of some prime examples: E.g. the precise measurement of the $^{27}$Al(n,2n)$^{26}$Al excitation function. In addition, a brief overview on detection limits and applications for a variety of long-lived radionuclides will be presented.

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## [157] Measurements of Total Cross Sections at Pohang Neutron Facility

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The Pohang Neutron Facility, which consists of an electron linear accelerator, a water-cooled Ta target with a water moderator, and a time-of-flight path with an 11 m length has been operated since 2000. We report the status activities on the neutron total cross-section measurements in the neutron energy region from 0.01 eV to 100 eV by the neutron time-of-flight method at Pohang Neutron Facility. A $^{6}$Li-ZnS(Ag) scintillator with a diameter of 12.5 cm and a thickness of 1.5 cm has been used as a neutron detector. The background level has been determined by using notch-filters of Co, Ta, and Cd sheets. In order to reduce the gamma rays from a Bremsstrahlung and that from a neutron capture, we have employed a neutron-gamma separation system based on their different pulse shape. The present measurements are compared with the previous ones and the evaluated data in ENDF/B-VI. The resonance parameters for several samples (Ag, Ta, and Hf) have been extracted from the transmission data by using the SAMMY code and compared with the previous ones.

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## [23] Nuclear level densities of $^{56}$Co, $^{57}$Co, $^{90}$Nb, $^{94}$Nb from neutron evaporation spectra

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Excitation functions, neutron spectra and angular distributions in (p,n) reaction on isotopes of $^{56}$Fe, $^{57}$Fe, $^{90}$Zr, $^{94}$Zr have been measured in proton energy range of (7-11) MeV. The measurements were performed by time-of-flight fast neutron spectrometer on the pulsed tandem accelerator EGP-15 of IPPE [1]. The high resolution ($\sim$0.6 ns/m) and stability of time-of-flight spectrometer allowed to identify reliably the discrete low-lying levels together with continuum part of neutron spectra. Analyses of the measured data have been carried out in the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The calculations are done with computer code GNASH using the generalized superfluid model of nucleus, back-shifted Fermi-gas model and composite formula of Gilbert and Cameron for nuclear level density. The nuclear level densities of $^{56}$Co, $^{57}$Co, $^{90}$Nb and $^{94}$Nb, their energy dependences and model parameters have been determined. In energy dependences of the nuclear level density of $^{56}$Co and $^{90}$Nb in excitation energy range between well-known low-lying levels and continuum part of excitation spectra is displayed the structure connected with the shell unhomogeneties of a single-particle state spectrum for nuclei near filled shells. This effect for magic nuclei was marked already in our work [2]. It is shown also that the obtained experimental data differ essentially from the predictions of nuclear level density model systematics.

1. V.G.Demenkov, B.V.Zhuravlev, A.A.Lychagin, V.I.Milshin, V.I.Trykova. Instruments and Experimental Techniques, (1995), V.38, N.3, p.314-318.

2. B.V.Zhuravlev, A.A.Lychagin, N.N.Titarenko, V.G.Demenkov, V.I.Trykova. Izv.RAN, ser. fizicheckaya, (2003), V.67, N1, p.98-102.

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## [489] Search for Subthreshold Neutron Production in Be

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There has long been interest in photoneutrons from Be, which has the lowest threshold known for any stable target. We have recently made a search for neutrons directly produced by the photon-induced 3-body breakup in $\gamma +^9 \mathrm{Be} \rightarrow \alpha + \alpha + \mathrm{n}$. The photons were obtained from a 2-MV electron Van de Graaf accelerator and allowed to irradiate a target of beryllium metal located at the center of a moderated detector array consisting of 30 10-atm $^3$He proportional counters. The photoneutron production was recorded as the bremmstrahlung end point was varied from 1.5 MeV to 1.8 MeV, encompassing the region from above the 2-body threshold in the reaction $\gamma +^9 \mathrm{Be} \rightarrow^8 \mathrm{Be} + \mathrm{n}$ to well below the energy needed for direct 3-body break up. A null result was obtained in contradiction to the previously reported experiment of Fujishiro *et al.* [M. Fujishiro, K. Okamoto, and T. Tsuijimoto, Can. J. Phys. **60** 1672 1983].

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# Nuclear Data Evaluations

**Anasazi North**, Tuesday 10:30–12:10

[530] Overview of Recent Bruyères-le-Châtel Actinide Evaluations
**B. Morillon [Invited]**

[544] Nuclear Data Evaluations for JENDL High-Energy File
**Y. Watanabe [Invited]**

[521] Recent General Purpose Evaluations for the JEFF Library
**H. Vonach [Invited]**

# Fundamental Measurements

**Anasazi South**, Tuesday 10:30–12:10

[486] Nuclear/Particle/Astrophysics with Slow Neutrons
**M. Snow [Invited]**

[501] Washing Up with Hot and Cold Running Neutrons: Tests of Fundamental Physical Laws
**S.K. Lamoreaux [Invited]**

[508] Standard-Model Tests with Superallowed $\beta$ Decay: Nuclear Data Applied to Fundamental Physics
**J.C. Hardy [Invited]**

# Measurements of Cross Sections

**Sunset**, Tuesday 10:30–12:10

[227] Minor Actinide Transmutation-Incineration Potential Studies in High Intensity Neutron Fluxes
**A.A. Letourneau**

[244] Measurements of Neutron Spectra Produced from a Thick Iron Target Bombarded with 1.5 GeV Protons
**S. Meigo**

[258] Excitation Functions for the Production of 10-Be, 26-Al, 129-I and 36-Cl in the Reaction $^{nat}$Pb(p,xn/yp)Z with Proton Energies up to 2.6 GeV
**D. Schumann**

[286] New Measurement of the Capture Cross Section of Bismuth and Lead Isotopes
**C. Domingo-Pardo**

[398] Measurement of Gas and Volatile Elements Production Cross Sections in a Molten Lead-Bismuth Target
**L. Zanini**

## [530] Overview of recent Bruyères-le-Châtel actinide evaluations

Maria-Jose Lopez-Jimenez, Pascal Romain, Benjamin Morillon

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Over the last five years, new evaluations of plutonium and uranium have been performed at Bruyères-le-Châtel from the resolved resonance region up to 30 MeV. Only nuclear reactions models have been used to build these evaluations. Total, shape elastic and direct inelastic cross sections are obtained from a coupled channel model using a dispersive optical potential devoted to actinides. All the other cross sections are calculated owing to the Hauser-Fesbach theory. We take particular care over the fission channel. For uranium isotopes, a triple-humped barrier is required in order to reproduce accurately the variations of the experimental fission cross sections. With increasing neutron incident energy, a lot of residual nuclei produced by nucleon emission lead to fission also. All available experimental data assigned to the various fission mechanisms of the same nucleus are used to define its fission barrier parameters. As a result of this approach, we are now able to provide consistent evaluations for a large series of isotopes. Integral data testing results of our new evaluations will be presented.

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## [544] Nuclear data evaluations for JENDL high-energy file

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High-energy cross section data above 20 MeV are required for various applications involving high-energy neutrons and protons, *e.g.*, accelerator-driven transmutation of nuclear waste and energy production, radiotherapy of cancer, and soft-error effects in microelectronics, *etc.* In this report, an overview is presented of recent nuclear data evaluations performed for the JENDL high-energy (JENDL-HE) file, in which neutron and proton cross sections for energies up to 3 GeV will be stored for 132 nuclides. The current version of the JENDL-HE file contains neutron total cross sections, nucleon elastic scattering cross sections and angular distributions, non-elastic cross sections, production cross sections and double-differential cross sections of secondary light particles ($n$, $p$, $d$, $t$, $^3$He, $\alpha$, and $\pi$), isotope production cross sections, and fission cross sections. The evaluations are performed on the basis of experimental data and theoretical model calculations. Since the experimental data are not enough in the incident energy region above 20 MeV, particularly for neutron-induced reactions, the nuclear model calculations play an important role in the high-energy cross section evaluations. We have developed a hybrid calculation code system utilizing some available nuclear model codes and systematics-based codes. A major code used for the intermediate energy range below 150 to 250 MeV is the GNASH code which is based on statistical Hauser-Feshbach plus preequilibrium exciton models. Optical model calculation codes such as ECIS and OPTMAN are also employed. For higher incident energy range, we use a microscopic simulation code (either JQMD or JAM) based on the quantum molecular dynamics or the intra-nuclear cascade model for dynamical processes and the evaporation model for the following statistical decay processes. The systematics-based codes, TOTELA and FISCAL, are also used for total, elastic scattering and reaction cross sections and angular distributions of elastic scattering, and fission cross sections. The evaluated cross sections are compared with the available experimental data and the other evaluations, with a focus on the influences of recent relevant measurements on the present evaluations. Future plans of our JENDL-HE project are also discussed along with prospective needs of high-energy cross section data.

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## [521] Recent General Purpose Evaluations for the JEFF Library

Herbert Vonach

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Starting with a discussion of the requirements and goals for high quality general-purpose evaluations, the paper will describe the procedures chosen in our evaluation work for JEFF for producing new general purpose evaluations with complete covariance information for all cross sections (file 3 data). Key problems essential for the goal of making the best possible use of the existing theoretical and experimental

knowledge on neutron interactions with the respective nuclide will be addressed, especially the problem of assigning covariances to calculated cross sections, necessary checking procedures for all experimental data and various possibilities to amend the experimental data base beyond the obvious use of EXFOR data for the respective cross sections. In this respect both the use of elemental cross sections in isotopic evaluations and the use of implicit cross section data (that is data which can be converted into cross sections by simple methods) will be discussed in some detail.

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## [486] Nuclear/Particle/Astrophysics with Slow Neutrons

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There are a number of unsolved scientific questions in nuclear, particle, and astrophysics which can be addressed with measurements using slow neutrons. I will give a brief overview of a selection of these questions and some examples of forthcoming experiments at LANSCE and NIST and planned experiments at the SNS. I will also briefly describe the LENS neutron source under constuction at Indiana and indicate how this source can be used to support research relevant to this area of science.

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## [501] Washing Up with Hot and Cold Running Neutrons: Tests of Fundamental Physical Laws

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The properties of the Neutron and its interactions with matter have been long applied to tests of fundamental physical principles. An example of such an application is a tests of the stability of the fundamental constants of physics based on possible changes in low-energy absorption resonances and the isotopic composition of a prehistoric natural reactor that operated two billion years ago in equatorial Africa. A recent re-analysis of this event indicates that some fundamental constants have changed. The focus of the presentation will be on the uses of cold and ultacold neutrons (UCNs), and in particular, the experimental search for the neutron electric dipole moment (EDM) which would be evidence for time-reversal asymmetry in the microscopic interactions within the neutron. Ultracold neutrons are neutrons with kinetic energy sufficiently low that they can be reflected from material surfaces for all angles of incidence, allowing UCNs to be stored in material bottles for times approaching the beta decay lifetime of the neutron. Vagaries associated with the production, transport, and storage of UCNs will be described, and an overview progress on development of a new neutron EDM experiment to be operated at LANSCE will be presented. This new experiment has potential to improve the measurement sensitivity by a factor of 100. Although an EDM has not be observed for any elementary particle, experimental limits have been crucial for testing extensions to the so-called Standard Model of Electroweak Interactions. Our anticipated sensitivity will be sufficient to address questions regarding the observed matter-antimatter asymmetry in the Universe.

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## [508] Standard-Model Tests with Superallowed $\beta$ Decay: Nuclear Data Applied to Fundamental Physics

J. C. Hardy

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Superallowed nuclear $\beta$ decay is a sensitive probe of the Electroweak Standard Model. The strength ($ft$-value) of a superallowed $\beta$ transition between $0^+$ analog states yields a direct measure for the vector coupling constant, $G_V$. Comparison of results for $G_V$ obtained from such transitions over a wide range of nuclei tests the conservation of the vector current (CVC), and comparison of the nuclear result with those obtained from the weak decays of K and B mesons tests another fundamental tenet of the Standard Model: the unitarity of the Cabibbo-Kobayashi- Maskawa (CKM) matrix. Current world data support CVC at the 0.04% level but show a $2.3\sigma$ deviation from CKM unitarity of 0.32%. This latter discrepancy could indicate the need for new physics and its discovery has stirred considerable activity directed at reducing the experimental uncertainties and arriving at a more statistically definitive result.

Any $ft$-value depends on three measured quantities: the Q-value, half-life and branching-ratio for a particular $\beta$ transition. To contribute usefully to the CKM unitarity test, an $ft$-value must be determined to $\sim$0.1%, which means that each of its three component quantities must be determined even more precisely. This demands that metrological techniques, in some cases with unprecedented precision, be applied to short-lived ($\sim$1s) activities; and that strict standards be employed in surveying the body of world data. The talk will overview the current status of these important tests, describe current experimental activity and indicate where broader nuclear data can play a key role.

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## [227] Minor Actinide transmutation-incineration potential studies in high intensity neutron fluxes.

Alain A. LETOURNEAU[1], Sébastien S. CHABOD[1], Yann Y. FOUCHER[1], Frédéric F. MARIE[1], Danas D. RIDIKAS[1], Christian C. VEYSSIERE[1], Christophe C. BLANDIN[2], Herbert H. FAUST[3], Paolo P. MUTTI[3], Ilham I. ALMAHAMID[4]

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An intensive program dedicated to the transmutation-incineration potential studies of Minor-Actinides in very intense neutron fluxes, namely the Mini-INCA project, has been initiated since few years at the French Atomic Agency (CEA). It deals with the development of new experimental techniques adapted for the very high neutron fluxes to measure the nuclear parameters of interest (capture and fission cross sections) as well as the transmutation and incineration potentials of actinides in a well characterised neutron flux.

For this purpose we have installed a calibrated alpha and gamma-spectroscopy station at the high flux reactor of ILL (Grenoble-France) allowing a quasi on-line measurement of the thermal neutron capture cross sections. In parallel, we are developing very small fission-chambers, namely micro fission-chambers, allowing a direct measurement of the thermal neutron-induced fission cross section and thus the incineration potential of the irradiated actinides. These fission-chambers are placed very closed from the fuel element allowing an access to a neutron intensity as high as 1.5 $10^{15}$ n/cm$^2$/s with an epithermal component which does not exceed 15% of the total energy spectra. The advantages of these very high neutron fluxes is to get access to short-lived isotopes with low masses (few microgram) and thus low local perturbation of the flux.

The impressive recent results concerning the thermal neutron capture and neutron-induced fission cross sections and transmutation-incineration potentials of $^{241,243}$Am, $^{239,242}$Pu, $^{237,238}$Np and $^{232}$Th, $^{233}$Pa will be presented and discussed. The analysis methods and recent developments concerning triple coupled micro fission-chambers will also been developed.

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## [244] Measurements of Neutron Spectra Produced from a Thick Iron Target Bombarded with 1.5 GeV Protons

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For the validation of the calculation code employed in the design of the pulse spallation neutron source and the accelerator driven system, it is required the spectrum of neutrons produced from a thick target, which is longer than the mean free path of the outgoing particles. However, these experimental data were scarce for the projectiles with energy above 800 MeV. In this study, the spectrum of neutrons produced from an iron target was measured to estimate the source of the neutron produced from the beam dump and the magnet. Furthermore, these experimental data were compared with the results calculated with NMTC/JAM.

The experiment was performed at carried out at the $\pi 2$ beam line of the 12-GeV proton synchrotron at KEK. Incident particles were supplied as the secondary particle generated by an internal target, which was placed in the 12-GeV proton beam. Spectra of neutrons produced from an iron target with 20 cm in thickness were measured, which was irradiated by 1.5 GeV protons. Measurements were performed by time-of-flight technique using NE213 scintillators. The flight time of the projectiles was also measured to identify the proton from other positive charged particles. The calculated result of NMTC/JAM and MCNP-4A was compared with the present experimental data. It is found that the NMTC/JAM generally gives a good agreement with experiment. Furthermore, the calculation gives good agreement with the experiment in the energy region between 20 and 80 MeV, whereas the NMTC/JAM gives 50

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## [258] Excitation Functions for the Production of 10-Be, 26-Al, 129-I and 36-Cl in the Reaction $^{nat}$Pb(p,xn/yp)Z with proton energies up to 2.6 GeV

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The design of accelerator driven system devices requires an accurate knowledge of the residue nuclei production within the spallation target. The long-term waste storage management has to consider long-lived isotopes which did not play an important part in the past but will, probably, contribute to the overall dose in waste containments of the future. Nuclides like 10-Be, 26-Al, 36-Cl and 129-I are difficult to determine due to their nuclear properties. The quantitativ measurements are carried out by accelerator mass spectrometry, a very sensitive but also time consuming method. Special chemical treatment of the irradiated targets is necessary to get the sample form required for the AMS measurement. Chemical separation procedures were developed which allow to isolate the iodine, chlorine, aluminium and beryllium fractions from the lead matrix. The cross sections of the four nuclides were determined, their excitation functions were calculated and compared with theoretical predictions. The work described here ist part of the HINDAS collaboration.

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## [286] New measurement of the capture cross section of bismuth and lead isotopes

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Lead and bismuth capture data are important in the field of energy production and nuclear waste transmutation, in order to evaluate the neutron balance in the core of an Accelerator Driven System (ADS) with Pb-Bi spallation target and also to account for the synthesis of $^{210m}$Bi through capture reactions, which determines the long term radiactivity of the spallation source.

In astrophysics, $^{208}$Pb and $^{209}$Bi represent the end point of the s-process, which by means of (n,$\gamma$) reactions builds around half of the isotopic abundances in the mass region A $\geq$ 56. Accurate capture data on these end point isotopes are required to further develop nucleosynthesis stellar modells and obtain heavy elements abundance predictions compatible with observations.

Capture in these isotopes is difficult to measure not only due to their small cross section but also due to the relatively high rate of scattered neutrons which can interact in the detector and surrounding material and mimic a capture signal. This has been a source of systematic uncertainty in previous experiments.

All the stable lead isotopes and $^{209}$Bi have been recently measured at n_TOF (CERN) in the range from 1 eV up to 1 MeV, using an optimized experimental setup. A set of two homemade $C_6D_6$ detectors with carbon fiber canning was designed to greatly reduce the scattered neutron sensitivity. Surrounding elements like the sample holder and the sample exchanger have been made also of carbon fiber.

The pulse height weighting technique, has been used in order to determine the (n,$\gamma$) cross sections. Concerning this technique, special care has been taken in the treatment of several sources of error leading to a total systematic uncertainty of less than 3%.

Results on the analysed $^{207}$Pb, $^{208}$Pb and $^{209}$Bi capture data and a comparison with previous experiments and data bases will be presented.

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## [398] Measurement of Gas and Volatile Elements Production Cross Sections in a Molten Lead-Bismuth Target

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MEGAPIE is a project for a 1 MW liquid PbBi spallation source, to be built at the SINQ facility at the Paul Scherrer Institut, which will be an important step in the roadmap towards the demonstration of the ADS concept and high power molten metal targets in general. For a reliable and safe operation of the experiment, it is extremely important to evaluate the amount and type of gas and volatile elements which will be produced. Both stable (H, $^4$He and other noble gases) and radioactive isotopes (including Kr, I, Hg and Po isotopes) are of interest. Different design options are under consideration to deal with the gas produced during operation.

For a correct estimate of the production cross sections, a measurement with a liquid PbBi target and a proton beam of energy close to the one of MEGAPIE (575 MeV) is necessary. Such a measurement was performed at the ISOLDE facility at CERN, which offers the unique opportunity via its mass spectrometric analysis of the elements present in the gas phase above the target to measure the production rate of several volatile elements produced in a liquid PbBi sample, after interaction of a proton beam with energy of 0.6, 1 or 1.4 GeV. Measurement techniques include detection with a Faraday cup, on-line $\gamma$ counting with the ISOLDE monitoring tape station, and collection on a foil and off-line $\alpha$-, $\beta$- and $\gamma$-spectroscopy. From the obtained yields, cross sections were deduced taking into account the ion source efficiency and other known correction factors.

The results from the measurements and from Monte Carlo simulations of the experiment, and their impact on the design of MEGAPIE will be discussed.

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# Application: Medicine

**Anasazi North**, Tuesday 13:30–15:30

[177] New Intermediate Energy Data for Medical Applications
**S.M. Qaim [Invited]**

[493] Nuclear Data in Radiation Therapy and Cancer Prevention
**J.F. Dicello [Invited]**

[310] Modelling Radiation-Induced Cellular Damage: Nuclear Models and Data Needed for Radiation Protection and Hadrontherapy
**F. Ballarini [Invited]**

[ 47] Reference Dosimetry for Fast Neutron and Proton Therapy
**D.T. Jones**

# Measurements of Cross Sections

**Anasazi South**, Tuesday 13:30–15:30

[516] Simulated (n,f) Cross Sections on Various Th, U, Np, Pu, and Am targets
**W. Younes [Invited]**

[528] An Overview of DANCE: A $4\pi$ $BaF_2$ Detector for Neutron Capture Measurements at LANSCE
**J.L. Ullmann [Invited]**

[434] Fission of Actinides induced by Neutrons at n-ToF
**L. Tassan-Got**

[375] Surrogate Neutron-induced Reaction Cross Section Measurements using STARS
**L.A. Bernstein**

# In Memory of S. Pearlstein

**Sunset**, Tuesday 13:30–15:30

[529] Contributions of Sol Pearlstein to Nuclear Data
**C. Dunford [Invited]**

[173] Historical Overview of Nuclear Data Evaluation in Intermediate Energy Region
**T. Fukahori [Invited]**

[520] Department of Energy Nuclear Criticality Safety Program
**J.R. Felty [Invited]**

[494] Average Total Capture Widths of Neutron Resonances
**S.F. Mughabghab [Invited]**

## [177] NEW TRENDS IN NUCLEAR DATA RESEARCH FOR MEDICAL APPLICATIONS

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Radioactivity has the unique character of being useful in medicine both for diagnosis and therapy. Whereas in diagnosis suitable $\gamma$-ray or positron emitters are needed for application in Single Photon Emission Tomography (SPECT) or Positron Emission Tomography (PET), for therapy, especially internal radiotherapy, soft but highly ionising radiation emitting radionuclides are required. Therapy is also performed with hadrons. This review describes briefly some recent developments and new directions in nuclear data research related to both diagnosis and therapy.

The production and decay data of all the commonly used SPECT and PET radionuclides are generally well known, and are also well documented. A new trend involves the use of longer-lived positron emitters, with one or the other of the following objectives:
(a)to study slow biological processes
(b)to quantify a new SPECT agent via analogue approach
(c)to optimise dosimetric calculations with regard to therapy planning
The development of a new positron emitter demands considerable work on charged particle induced nuclear reactions to be able to choose an appropriate production route. Some recent studies related to the development of the positron emitters $^{124}$I ($T_{1/2}$ = 4.2 d), $^{94m}$Tc ($T_{1/2}$ = 52 min) and $^{86}$Y ($T_{1/2}$ = 14.7 h) will be described as typical examples. The formation of isomeric states constitutes a new challenge, not encountered in the production of commonly used PET radionuclides. Appreciable effort is also involved in determining the exact decay data of the new positron emitter, particularly the positron branching ratio, the average positron energy and the $\gamma$-rays associated with the decay, especially when quantitative PET-imaging is the aim. For production of most of the longer-lived positron emitters a 40 MeV cyclotron may be adequate. However, in some cases data in the intermediate energy range up to 100 MeV are needed. In a few rare instances, for example search for positron emitters in the region of rare earths, even exotic heavy-ion and spallation reactions are being considered.

As far as hadron therapy is concerned, atomic and molecular data are of primary concern. The nuclear data generally pertain to scattering and neutron and charged particle emission processes. For energies up to 200 MeV those data are generally well-documented; they can also be calculated rather well. In contrast, there has been some lack in the availability of activation data in proton therapy. A recent study on the formation of short-lived positron emitters in the tissue under proton therapy conditions will be described.

The therapeutic radionuclides are generally produced in a nuclear reactor and the data are known well, though not properly evaluated and organised. Enhanced efforts have been devoted in recent years to development of radionuclides for internal radiotherapy, generally low-energy $\beta^-$ emitters or Auger electron emitters. Nuclear reaction cross section measurements for the formation of those radionuclides, especially via charged particle induced reactions, are rather challenging. Here interdisciplinary techniques of sample preparation and radioactivity measurement (x-ray spectrometry, liquid scintillation counting etc.) are needed. The very promising therapeutic radionuclide $^{225}$Ac is obtained by processing of burnt up fuel. An alternative route involves handling of a radioactive target. The production of some conventional therapeutic radionuclides using a fast neutron spectral source has also been considered: A brief review of all those developments will be given.

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## [493] Nuclear Data in Radiation Therapy and Cancer Prevention

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The nuclear sciences and technologies continue to exert a major impact on health and medicine, both directly in terms of developing new modalities and treatments, and indirectly in terms of showing the advantages of improved approaches, leading the way for improved standards of care with conventional modalities. Most notable in therapy has been the successful application of beams of nuclear particles to radiation therapy, which demonstrated that precise dose localization could produce major improvements in disease control with reduced negative consequences. Throughout the world energetic protons, heavier ions, and neutrons are being used to treat cancers and other diseases, and new clinical facilities are being built. The design and construction of these machines as well as their clinical application require precise nuclear data. Successful localization of beams to complex treatment volumes for therapy demands detailed imaging of the anatomical structures and tissues as well as their cellular and subcellular characteristics. The contributions to diagnostic medicine of improved imaging and tomography based upon nuclear

technologies are generally well known; however, the more recent incorporation of such methods into routine therapy is perhaps less appreciated. The large amount of input data along with increasingly more complex delivery systems in radiation therapy in turn require more accurate, more complex, more sophisticated treatment planning. Today, real-time imaging, planning, and verification are being done during treatment. Although analytical approaches have dominated this area of medicine, Monte Carlo methods have always offered a potential advantage which has never been fully realized, at least until recently. With improved calculational abilities and more extensive and more accurate nuclear and atomic data, Monte Carlo treatment planning is a major research topic with commercial products beginning to move into the marketplace. In any case, accuracy and efficiency remain serious limitations, where any approach can be successful in the clinic only if the service can be performed at a cost that is consistent with limits set by Federal health care and major providers. (The failure to translate successes in research laboratories to the clinic is recognized as a serious national problem and is being addressed at every level).

As stated previously, many of the biomedical advances have arisen in diagnostic medicine and, therefore, have contributed toward improved public health and prevention at least as much as therapy. Perhaps one of the most interesting applications has occurred in risk assessments and disease prevention for astronauts. Personnel in space receive significant doses from radiations, and it is considered one of the major biomedical hazards of long-term missions. Initially we possessed neither sufficient biological information nor cross-sectional data of sufficient accuracy to adequately estimate the risks. The new NASA Space Radiation Laboratory at Brookhaven has recently been commissioned, ushering in a new era of biomedical research in this field. The scientific issues, the research, and the history leading to this new facility exemplifies the potential success of collaborative ventures on the part of scientists and administrators from diverse fields, with physical and biological dosimetry playing a major role. Finally, the role of the Radiation Effects Team of the National Space Biomedical Research Institute in not only using physical and biodosimetric means to evaluate the risks from Space radiations but also showing the feasibility of pharmaceutical countermeasures after exposures will be reviewed.

Funded in part from NASA Project RE00203 award from the National Space Biomedical Research Institute.

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## [310] Modelling radiation-induced cellular damage: nuclear models and data needed for radiation protection and hadrontherapy

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Tumour treatment with protons and Carbon ions is now performed by an increasing number of facilities since it can allow for a better optimisation of Tumour Control Probability and Normal Tissue Complication Probability, particularly for radioresistant tumours. Moreover, protons and heavier ions are of concern in particular radiation protection scenarios such as exposure to space radiation. Nuclear interactions with the beam line components (for hadrontherapy), the spacecraft walls (for space radiation protection) and the human body can significantly modify the radiation field.

The FLUKA transport code, integrated with radiobiological data and coupled to anthropomorphic phantoms, is applied to the characterisation of therapeutic proton beams and the calculation of space radiation organ doses. Besides absorbed doses, quantities more directly related to biological damage (often referred to as "biological doses") can be calculated. In this work the "biological dose" is modelled as the yield of "complex lesions", which are clustered DNA breaks.Very good agreement was found with experimental data obtained at the OPTIS proton therapy facility. The relative contribution of nuclear reaction products was higher for the "biological dose" than for the absorbed dose, mainly due to the higher biological effectiveness of target fragments. The effects of Galactic Cosmic Rays and Solar Particle Events were simulated as a function of the shield thickness. Again, the nuclear reaction products provided a larger relative contribution to the "biological dose" than to the absorbed dose. While SPE doses decreased by increasing the shield thickness, GCR doses showed more complicated trends due to the higher complexity of the radiation spectrum.

Since Complex Lesions can evolve into chromosome aberrations (which are correlated with cell death and oncogenic transformation), a model and code simulating aberration induction was developed, also

in view of an interface to FLUKA. The model predicts dose-response curves for the main aberration categories induced in human cells by different radiation types, both as monochromatic and as mixed fields. The very good agreement with data provided a validation of the model, confirming the fundamental role of energy deposition clustering at the nanometer and micrometer levels.

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## [47] Reference dosimetry for fast neutron and proton therapy

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In radiation therapy tumour control and normal tissue complication probabilities are both steep functions of absorbed dose which must therefore be accurately and reproducibly determined. Accuracy of ±3% is desirable, while reproducibility of ±2% is required. The requirements for a dosimeter depend on: the accuracy of the absorbed dose determination required; the sensitivity of the measuring system; the energy dependence of the dosimeter response; the spatial resolution required.

Fast neutrons and protons undergo fundamentally different interactions in tissue. The former interact with nuclei, while the latter, as in the case of photons, interact mainly with atomic electrons. Protons do, however, also undergo some nuclear interactions, the probability of which increases with energy. For both modalities the practical instruments for determining the reference absorbed dose in a patient are thimble ionization chambers. These provide indirect determination of absorbed dose as calibration factors measured in standard radiation fields as well as conversion factors which require knowledge of various physical data, have to be applied. In principle calorimeters give a direct determination of the absorbed dose (the energy imparted to a sensor is indicated by a temperature change) and therefore yield the smallest uncertainty, but they are not practical instruments for routine clinical use.

Several dosimetry protocols for both fast neutron and proton therapy have been published. All the protocols cecommend that, in the absence of a calorimeter, reference absorbed dose measurements in the clinical situation be made with ionization chambers having Co-60 calibration factors traceable to standards laboratories. The calibration factors can be given in terms of exposure, air kerma or absorbed dose to water. The latter is preferred as the uncertainties in the chamber-dependent factors used to convert measurements to absorbed dose are less, the formalism is simpler and easier to interpret and the probability of error is less.

Because of the nature of neutron interactions tissue-equivalent ionization chambers are used for neutron dosimetry The situation is complicated by the fact that neutron beams are always contaminated with gamma rays, which need to be accounted for. The universally accepted protocol was published as long ago as 1977 by the International Commission on Radiation Units and Measurements (ICRU) [1]. Proton dosimetry is inherently simpler and ionization chamber composition is not critical. In 1998 the ICRU also published a proton dosimetry protocol [2] which was adopted by most proton therapy centres. More recently the International Atomic Energy Agency (IAEA) published a proton dosimetry code of practice [3] using a formalism applicable to all therapy modalities (except neutrons).

The three protocols above will be descibed and discussed and the two proton protocols will be compared. Details of the measuring procedures, the formalisms and the physical quantities required to convert the measurements to absorbed doses will be given, together with estimates of the uncertainties.

The dosimetry of fast neutron and proton therapy beams is on a sound footing and meets internationally accepted standards.

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## [516] Simulated (n,f) cross sections on various Th, U, Np, Pu, and Am targets.

W. Younes

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Fission probabilities, measured in (t,pf), ($^3$He,df), and ($^3$He,tf) reactions, have been interpreted using a detailed model to estimate neutron-induced fission cross sections on a variety of actinide targets. Particular emphasis has been placed on a proper accounting of spin and parity transferred in

the reactions, and on modern calculations of transmission coefficients. Using this "surrogate" technique, (n,f) cross-section estimates have been obtained to within 10% uncertainty on targets of $^{231,233}$Th, $^{234,235,235m,236,237,239}$U, and $^{240,241,243}$Pu, for equivalent neutron energies up to $E_n = 2.2$ MeV [1,2], and on targets of $^{236,236m,237,238}$Np, $^{237,237m}$Pu, and $^{240,241,242,242m,243,244,244m}$Am up to $E_n = 6$ MeV [3]. Of particular interest to the program, we have extracted the (n,f) cross section on the $^{235}$U 26-minute isomer at 77 eV of excitation energy, and the $^{237}$U(n,f) cross section, for which we have released a preliminary estimate up to $E_n = 20$ MeV, based on surrogate (t,pf) data. For some actinide targets, we have provided cross sections that cannot be measured in any other way. In the remaining cases, our results improve on or confirm previous estimates.

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## [528] An Overview of DANCE: A 4$\pi$ $BaF_2$ detector for Neutron Capture Measurements at LANSCE

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The Detector for Advanced Neutron Capture experiments (DANCE) is a 162-element, 4$\pi$ $BaF_2$ array designed to make neutron capture cross-section measurements on rare or radioactive targets with masses as little as 1 mg. Accurate capture cross sections are needed in many research areas, including stellar nucleosynthesis, advanced nuclear fuel cycles, waste transmutation, and other applied programs. These cross sections are difficult to calculate accurately and must be measured. Up to now, except for a few long-lived nuclides there are essentially no differential capture measurements on radioactive nuclei. The DANCE array is located at the Lujan Neutron Scattering Center at LANSCE, which is a continuous-spectrum neutron source with useable energies from below thermal to about 100 keV. Data acquisition is done with 320 fast waveform digitizers. The design and initial performance results, including background minimization, will be discussed.
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## [434] Fission of Actinides induced by Neutrons at n-ToF

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The development as well as the design of new nuclear reactors require a more precise knowledge of nuclear data than presently available. Among urgent needs are fission cross sections of actinides which had not been measured with high precision in the past, since they were of minor importance for the present nuclear reactors. The n-ToF facility at CERN allows precise measurements due to its long flight path (185 m) and its high neutron flux delivered in a very short time, particularly interesting for the study of radioactive isotopes.

Fission cross sections are obtained by detecting the two fission fragments in coincidence with PPAC detectors (Parallel Plate Avalanche Counters). Such coincident measurements are interesting in particular at high neutron energies because they allow to disentangle fission from other reactions which start to appear at neutron energies above a few MeV. As a matter of fact, our fission measurements have been realized from 1 eV till energies above 100 MeV.

Measurements have been performed first for isotopes which are of interest for the thorium cycle : $^{232}$Th, $^{233}$U, $^{234}$U. In addition $^{nat}$Pb and $^{209}$Bi have also been measured as they might be important for subcritical reactors in which they could be used as spallation targets and for cooling. Concerning minor actinides $^{237}$Np has also been measured. All measurements are performed in reference to $^{235}$U and $^{238}$U permanently present in the stack of targets.
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## [375] Surrogate Neutron-induced Reaction Cross Section Measurements using STARS

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Reactions on unstable nuclei are at the core of nucleosynthesis in environments from stars to supernovae to the interior of nuclear weapons. However, the cross sections for many of these reactions are difficult to predict due to the presence of nuclear structure effects and unusual decay modes, and equally difficult to measure due to the short lifetimes of the radioactive species involved. The LLNL group is leading an effort to deduce these cross sections using a technique referred to as the surrogate reaction method. The surrogate method involves measuring the particle and g-ray decay probabilities of highly excited nuclei with a well-defined excitation energy and spin distribution populated via a transfer reaction. These measured probabilities can then be combined with neutron optical model calculations to produce equivalent neutron-induced reaction cross sections. In this talk I will present results from two experiments using the surrogate reaction technique. The first experiment used the STARS (Silicon Telescope Array for Reaction Studies) spectrometer coupled to GAMMASPHERE to successfully reproduce surrogate (n,$\gamma$), (n,n') and (n,2n) cross sections on $^{156,155}$Gd using $^{3}$He-induced reactions. The second experiment performed at the Wright Nuclear Structure Lab at Yale University using STARS coupled to the YRAST ball g-ray array used 3He-induced reactions as surrogates for the $^{90,91}$Zr(n,x$\gamma$) reactions. The results from this experiment will be compared to recent work by Garrett et al., where $^{90}$Zr(n,xn yp z$\alpha\gamma$ reactions were measured using the GEANIE spectrometer [1]. This experiment is of particular interest since the population of discrete states in the residual nuclei populated using $^{3}$He and neutrons can be compared providing insight into spin differences between the two reactions. The implications of this data for the surrogate reaction technique will be presented and competition between equilibrium and pre-equilibrium reaction modes discussed.

[1] P.E. Garrett private communications

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## [529] Contributions of Sol Pearlstein to Nuclear Data

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The late Sol Pearlstein was a pioneer and leading figure in the field of nuclear physics data that is fundamental to progress in both applied nuclear technology and basic nuclear physics research. As the first head of the United States National Nuclear Data, he was responsible for organizing the United States nuclear data evaluation work and the production of the Evaluated Nuclear Data File (ENDF). Sol was a strong supporter of collaborative science both nationally and internationally. He was the driving force behind the international efforts to compile nuclear reaction data and to evaluate nuclear structure and radioactivity data, activities that continue to this day to be a crucial component of the world's nuclear data activities. This paper will review Sol's contributions to the field of nuclear data.

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## [173] Historical Overview of Nuclear Data Evaluation in Intermediate Energy Region

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In recent years, intermediate energy nuclear data are required for various applications such as accelerator-driven systems for nuclear waste transmutation, spallation neutron sources, advanced cancer therapies with particle beams, estimation of single event up set rate and dose on astronauts, and so on. Proton and photon data as well as neutron data are necessary in these intermediate energy applications. To meet these requirements, many groups in the world continue some activities concerning nuclear data evaluation in the energy range above 20 MeV, which is the upper limit of conventional general purpose evaluated nuclear data files.

The early stage of nuclear data evaluation in the intermediate region was initiated in USA. For example, Pearlstein at National Nuclear Data Center, Brookhaven National Laboratory produce some systematics, modified ALICE code produced by Blann and evaluated proton and neutron intermediate nuclear data of Fe-56 in late 1980s. At Lawrence Livermore National Laboratory, the intermediate nuclear data also developed for a medical application in nearly the same period. Following these efforts, many countries, such as Europe, Japan, Russia, People Republic of China, Korea, started the preparation of nuclear data in this energy region.

Nuclear data evaluation is generally carried out on the basis of experimental data and theoretical model calculations. However, the experimental data are sparse for neutron-induced reactions in the intermediate energy region and systematic measurements are not enough for proton data. Therefore, theoretical model calculations play a major role in the intermediate energy nuclear data evaluation. The statistical model with correction of pre-equilibrium process is mainly applied in the intermediate energy region. For energies higher than 150 MeV, the Quantum Molecular Dynamics (QMD) plus statistical decay model and the intranuclear cascade (INC) plus generalized evaporation model (GEM) are employed in Japan. The systematics based on experimental data is also applied for evaluation of total, elastic, proton reaction and fission cross sections for the intermediate energy region.

Overview of intermediate nuclear data evaluation methods, some results of the evaluations are presented in comparison between experimental data and evaluated files, mainly JENDL High Energy File, as well as some results from integral benchmark calculations.

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## [520] Department of Energy Nuclear Criticality Safety Program

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This paper broadly covers key events and activities from which the Department of Energy Nuclear Criticality Safety Program (NCSP) evolved. The NCSP maintains fundamental infrastructure that supports operational criticality safety programs. This infrastructure includes continued development and maintenance of key calculative tools, differential and integral data measurements, benchmark compilation, development of training resources, hands-on training, and web-based systems to enhance information preservation and dissemination. The NCSP was initiated in response to Defense Nuclear Facilities Safety Board Recommendation 97-2, *Criticality Safety,* and evolved from a predecessor program, the Nuclear Criticality Predictability Program, that was initiated in response to Defense Nuclear Facilities Safety Board Recommendation 93-2, *The Need for Critical Experiment Capability.* This paper also discusses the role Dr. Sol Pearlstein played in helping the Department of Energy lay the foundation for a robust and enduring criticality safety infrastructure.

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## [494] Average Total Capture Widths of Neutron Resonances

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During his tenure as director of the National Nuclear Data Center, Sol Pearlstein fully supported the project dealing with the publications of the third and fourth editions of *Neutron Cross Sections,* which are widely known as BNL-325. In particular, Sol was keenly interested in the systematic properties of

average resonance parameters, which were described in these editions. As a tribute to his memory, I will discuss in this session the progress achieved in our understanding of the average capture widths of neutron resonances in terms of theoretical models. This study is carried out within the framework of the generalized Landau-Fermi liquid model of the photon strength function, as developed by Mughabghab and Dunford (Phys. Lett., B, 487,155,(2000)). The theoretical predictions will be compared with the most recent evaluations of total average capture widths of nuclei, which will be reported in a forthcoming fifth edition of BNL-325. In addition, because of the sensitivity of the predictions to the nuclear level density parameters, the latter quantities will be discussed.

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# Application: Fuel Cycle, ADS

**Anasazi North**, Wednesday 8:30–10:10

[503] MYRRHA, A Multipurpose Accelerator Driven System for R&D. Need for New Nuclear Data ?
**H. Aït Abderrahim [Invited]**

[514] Innovative Nuclear Energy Systems and Related R&D Challenges
**M. Salvatores [Invited]**

[541] Thermal Spectrum for Nuclear Waste Burning and Energy Production
**C. Bowman**

[263] Effect of Anisotropic Scattering in $UO_2$ and MOX Fueled LWR Cells and Cores
**T. Takeda**

# Astrophysics and Cosmology

**Anasazi South**, Wednesday 8:30–10:10

[483] Nuclear Data for Astrophysical Nucleosynthesis: A Japanese + LANL Activity
**S. Chiba [Invited]**

[497] Research with Radioactive Beams at the TRIUMF-ISAC Facility
**J.M. D'Auria [Invited]**

[380] Future of Nuclear Data for Nuclear Astrophysics
**M. Smith**

[ 34] Stellar Neutron Capture Cross Sections of the Hf and Lu Isotopes
**K. Wisshak**

# Measurements and Facilities

**Sunset**, Wednesday 8:30–10:10

[487] Neutrons for Science and Industry — Uppsala Neutron Beam Activities
**J. Blomgren [Invited]**

[526] GEANIE Measurements of Neutron-Induced Partial $\gamma$-ray Cross Sections for Nuclear Data
**J.A. Becker [Invited]**

[240] Neutron and Light Charged Particle Production in Neutron or Proton Induced Reaction on Iron, Lead and Uranium at Intermediate Energy (20 to 200MeV) — The HINDAS Collaboration
**V. Blideanu**

[154] First Measurements with a Lead Slowing Down Spectrometer at WNR
**D. Rochman**

## [503] MYRRHA, A Multipurpose Accelerator Driven System for R&D. Need for New Nuclear Data ?

H. Aït Abderrahim

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The MYRRHA facility in planning has been conceived as a fast spectrum irradiation facility for various R&D applications complementary to the thermal spectrum RJH (Réacteur Jules Horowitz) facility, in planning in France. This situation would give Europe a full research capability in terms of nuclear R&D.

Furthermore, the disposal of radioactive wastes resulting from industrial nuclear energy production has still to find a fully satisfactory solution, especially in terms of environmental and social acceptability. As a consequence, most countries with significant nuclear power generating capacity are currently investigating various options for the disposal of their nuclear waste. Scientists are looking for ways to drastically reduce (by a factor of 100 or more) the radio-toxicity of the High Level Waste (HLW) to be stored in a deep geological repository, and to reduce the time needed to reach the radioactivity level of the ore originally used to produce energy. This can be achieved via the development of the Partitioning and Transmutation and burning MAs and to a less extent LLFPs in Accelerator Driven Systems. The MYRRHA project contribution will be in helping to demonstrate the ADS concept at reasonable power level and the demonstration of the technological feasibility of MA and LLFP transmutation under real conditions.

In this paper a resume for the choice of the basic parameters of MYRRHA and a description of the design achieved at the end of the pre-design phase of the project will be given. The author will be emphasizing the new needs for nuclear data as regard to the design needs as well as the transmutation in ADS.

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## [514] INNOVATIVE NUCLEAR ENERGY SYSTEMS AND RELATED R&D CHALLENGES

M. Salvatores

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Innovative Reactor Systems , including both reactor concepts and the associated fuel cycles, are presently under study in several leading countries, in order to cope with requirements for improved economics, waste minimisation, safety and sustainability. The GENERATION-IV initiative is an outstanding, but definitely not the only one, example.

In the present paper we will focus mainly on the waste management and sustainability aspects.

These two fields provide the frame for the deployment of innovative technologies, with significant scientific challenges. The full paper will discuss and compare several promising scenarios, in terms of Plutonium and Minor Actinide management, and it will be shown the transition from a waste minimisation primary objective, to a full sustainability scenario for nuclear power development.

Evolutionary and revolutionary concepts both for reactors and fuel cycles are included in these scenarios: new types of fuels; fuel reprocessing, molten salts technologies, innovative PWR concepts, gas cooled reactors, Accelerator driven Systems.

A few selected examples will be examined in the paper, indicating major scientific challenges and experiments needed to be performed in order to validate the concepts.

In particular in the area of ADS, basic experiments already performed or being planned (like the TRADE experiment) will be discussed.

The ADS field of research is a good example of multidisciplinary R&D needs in several areas: new fuels, dedicated to waste transmutation; liquid metal technology; nuclear physics; accelerator technology; reactor physics and technology of multiplying sub-critical reactor cores.

In each area, new requirements have to be fulfilled: fuels with a high content of minor actinides and U-free; material compatibility with, e.g., lead alloys under irradiation of both neutrons and protons; accurate nuclear data in the energy range above 20 MeV; high power proton accelerators with unusually stringent requirement for reliability; the effective coupling of a particle accelerator, a spallation target and a power reactor core; the dynamic behaviour and the reactivity control of a sub-critical core in presence of an external source.

Indications will be given of R&D areas of relevance, including nuclear data, and of ongoing R&D programs and expected results. In particular, a consistent European program (EUROTRANS) to be launched in this domain will be described.

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## [541] Thermal Spectrum for Nuclear Waste Burning and Energy Production

Charles D. Bowman

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The private sector has been the primary source of world-changing innovation for most areas of new technology development in the U. S for the past 50 years. We report here new options developed without government funding that extend the original Los Alamos ATW initiative and might offer a resolution to the problems of nuclear energy that government management has not been able to solve for decades.

*Continuous-flow molten-salt thermal-spectrum systems*

Several of our papers in refereed journals describe how continuous fuel flow eliminates the need for refueling downtime, enables breeding with the same effectiveness as fast spectrum reactors without reprocessing and fuel refabrication, eliminates the need for enrichment of any kind, and accomplishes the burning of existing spent fuel in a much shorter time scale and with much lower inventory and therefore many fewer systems than is possible with fast spectrum systems.

*Supplemental neutrons from deuterium gas targets*

We are exploring a new accelerator target that might provide neutrons at the same energy cost as spallation but with the advantages of much lower accelerator energy and the elimination of spallation products. A 100-MeV proton beam directed upon a deuterium gas target would collide with the deuterium to produce neutrons, fast moving deuterium ions that produce more neutrons by (d,d) reactions and also forward-moving fast tritium or 3He ions that produce even more neutrons and deuterons. The total process initiated is a forward directed cascade of all of the fusion reactions producing fast neutrons that may be multiplied by a surrounding blanket of Be or Pb

*Tailoring the thermal spectrum using graphite manufactured with lattice-stored energy*

Our efforts to understand anomalous neutron transport observed in experiments with large amounts of bulk granular graphite show that stored energy can be built into newly manufactured graphite. Neutrons moving through the graphite tap this energy with the result that the neutron spectrum from room temperature graphite can be adjusted from the expected 25 meV to 250 meV depending on the graphite production process. This change in spectrum by a factor of three in average neutron velocity implies 50–100% increases in the reaction rates for many nuclides of interest including $^{237}$Np, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{241}$Am, and $^{249}$Cf and lower absorption by three for graphite moderators and reflectors.

*Fusion for neutron production instead of energy production*

The ultimate purpose of reprocessing is to eliminate the waste of scarce neutrons on unproductive absorption. However reprocessing is proliferation-prone and has been found to be much more expensive than expected. It might be more economically practical to lose some neutrons wastefully and eliminate reprocessing if the cost of supplemental neutrons is low enough. It can be shown that long before fusion systems produce energy at costs competitive to fission, they will produce neutrons at a cost much lower than accelerators and thereby probably make practical subcritical systems with $k_{\text{eff}}$ perhaps as low as 0.50.

This paper calls for new effort in accelerator targets, molten salt technology, new graphite-based thermal-spectrum systems optimized to take maximum advantage of neutron spectrum control by stored-energy graphite, and new fusion research aimed at copious neutron production instead of economic fusion power. Pursuit of the advances presented here should enable a breakout of fission energy technology from present U. S. policy for incremental improvement to mature technology that has been economically and/or politically undeployable in this country and the world for decades. A list of nuclear data requirements will be included.

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## [263] Effect of Anisotropic Scattering in $UO_2$ and MOX Fueled LWR Cells and Cores

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The effect of anisotropic scattering in $UO_2$ and MOX fueled LWR cells and LWR cores on neutronic characteristics has been evaluated. First, let us consider infinite cells with $UO_2$ and MOX fuel. As a cross section, the 70-group cross section set obtained from the JENDL-3.2 data was used, and the cell calculations were performed based on the method of characteristics (MOC). The anisotropic scattering has been treated by expanding the scattering cross section using Legendre polynomial up to $P_5$. As cell models, various cells with $V_m/V_f$ of 1.0, 1.7 and 3.0 were considered. The cell with $V_m/V_f = 1.7$ corresponds to the conventional PWR cell. For the $UO_2$ fuel, the anisotropic scattering effect (the difference between $k_\infty$ values for $P_0$ and $P_5$ scattering) is small, and within 0.1 %. However, for the case of MOX fuel, the anisotropic scattering effect becomes 0.1 $\sim$ 0.2 % $\Delta k/k$, and is not negligible.

This large effect for the MOX cell is caused by the large neutron current in the moderator. The strong absorption of Pu leads to the large neutron current, and the scattering source term of the $P_1$ component is proportional to the product of neutron current and the $P_1$ component of the scattering cross section. So the anisotropic scattering effect is large for the MOX cell. For MOX fuel cells, the difference between $k_\infty$ values for $P_5$ and $P_0$ anisotropic scattering cases are $-0.146$, $-0.225$, $-0.200$ % $\Delta k/k$ for $V_m/V_f$ = 1.0, 1.7, and 3.0 respectively. The effect up to $P_3$ scattering is almost equal to that up to $P_5$ scattering (the difference is within 0.05 % $\Delta k/k$). So the anisotropic scattering effect up to $P_3$ scattering is enough to be considered for $k_\infty$ and other neutronic characteristics. The decrease of $k_\infty$ values due to anisotropic scattering effect is caused by the fact that neutrons passing the moderator towards the fuel in the lower energy range have moved more to the fuel due to forward scattering. Therefore the relative absorption rate in the fuel increases, and this leads to decrease of $k_\infty$ when considering the anisotropic scattering. Furthermore it is interesting to investigate the effect of the transport cross section. The Kinf values calculated using the transport cross section in the MOX fuel are larger than those of $P_0$ scattering cases by 0.216, 0.165, 0.062 % $\Delta k/k$ for the cases of $V_m/V_f$ =1.0, 1.7, and 3.0, respectively. This trend is opposite to the cases using $P_5$ scattering. So, one can say that the use of conventional transport cross section leads to erroneous results for the anisotropic scattering effect. The reason of this erroneous results and the results in 2-D core calculations will be shown in the presentation.

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## [483] Nuclear Data for Astrophysical Nucleosynthesis: A Japanese + LANL Activity

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Nuclear reactions, especially the neutron-induced reactions, play essentially important roles both in nuclear energy applications and astrophysical nucleosynthesis. In fact, about 99 % of elements heavier than the iron-nickel group in the solar system were synthesized by two successive neutron capture reaction chains, namely the s- and r-processes.

In the past, the nuclear-data and astrophysical communities have engaged in constructing databases on nuclear structure, reaction, and decay rates independently. There are many common features in the activities of these two communities, but both approaches have specific strengths and drawbacks that can be compensated by each other.

Here, we would like to present a status of a loosely-bound Japanese + LANL activity to generate a new database for astrophysical nucleosynthesis. As a new comer, we are currently putting emphasis on nuclear reaction rates for neutron-induced reactions (mostly by phenomenological methods), nuclear mass and $\beta$-decay rates covering some thousands nuclei needed for r-process calculations. However, special attention is also paid for, e.g., theoretical treatment of charged-particle reactions in light nuclei, properties of nuclei far off $\beta$-stability and high-density nuclear/hadron matter that determine the physical conditions of BBN and r-process nucleosynthesis cites.

The main contents of our activities are categorized as follows:

- Nuclear mass and related data (Waseda/Riken/JAERI)
- $\alpha$- and $\beta$-decay rates (Waseda/Riken/JAERI)
- Fission barrier and fission half lives (Waseda/Riken/JAERI)
- Neutron capture cross section calculations (LANL/JAERI)
- Fission yield calculations (Konan/JAERI)
- Reaction rates involving 3- and 4-clusters (JAERI/TUS/Kyushu)
- Measurements of important reaction rates (JAERI/TIT)
- Properties of supernova and neutron-star matter (JAERI/Kyoto)
- Astrophysical applications, interpretations and feedback to nuclear data (NAO/JAERI)

Summaries of these activities and future scopes will be presented at the conference.

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## [497] Research with Radioactive Beams at the TRIUMF-ISAC Facility

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The field of research with energetic radioactive beams from ISOL type systems is now well established and a number of facilities exist around the world. Such facilities provide a wide variety of accelerated beams of excellent quality and intensities to allow experimentation previously considered impossible. Indeed there are now proposals on the table in the U.S. and elsewhere to build facilities even bigger and better, e.g., RIA. Following an overview of the field, emphasis will be given in this presentation to the new TRIUMF-ISAC facility located in Vancouver, Canada and the various studies in progress or planned. In particular, studies in the area of experimental nuclear astrophysics using the unique DRAGON facility will be presented including the recently completed study of radiative proton capture on the radioactive species, $^{21}$Na. This rate of the reaction plays an important role in the explosive scenario such as ONe novae.

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## [380] Future of Nuclear Data for Nuclear Astrophysics

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Nuclear astrophysics research addresses some of the most fundamental and compelling questions in nature: What are the origins of the elements that make up our world? How did the solar system, the sun, the stars, and the galaxy form, and how do they evolve? Measurements and theoretical descriptions of microscopic nuclear physics phenomena provide the foundation for sophisticated models of these macroscopic astrophysical systems. These models are increasingly challenged by observations from space- and ground-based instruments that provide an incredibly detailed view of the Cosmos. The ability of astrophysical models to explain these observations strongly depends, in many instances, on the input nuclear data, and the latest models require more extensive and precise sets of nuclear data than ever before. In fact, progress in solving numerous astrophysical puzzles hinges on the availability of accurate, comprehensive sets of nuclear data that incorporate the latest laboratory measurements and theoretical results. Studies in this field can potentially bring wide public exposure to nuclear data activities.

The production of nuclear datasets for astrophysics requires dedicated efforts in data compilation, evaluation, processing, and dissemination. Unfortunately, the manpower base for this work is eroding just as the rate of production of new results is increasing. Furthermore, the process of converting laboratory results into entries in a database is currently quite complicated and requires the use of numerous computer codes and multiple steps (and often numerous individuals). For these reasons, some vital nuclear datasets have not been updated for over a decade, and it is often the case that datasets are not freely shared within the community. The wealth of data expected from future facilities such as the Rare Isotope Accelerator (RIA) will only to exacerbate this problem. Unfortunately, there is currently neither sufficient manpower nor an identified mechanism to rectify this situation. To make the best use of investments in nuclear astrophysics measurements, it is imperative to take action now to: increase evaluation manpower, in both the nuclear data and nuclear astrophysics communities; improve communication between ongoing evaluation centers, and between evaluators and the astrophysics end users; streamline the process of converting lab measurements into rates; and more efficiently manage and visualize nuclear astrophysics datasets. Possible mechanisms to achieve each of these goals will be presented, along with a description of some ongoing activities in these directions.

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## [34] Stellar Neutron Capture Cross Sections of the Hf and Lu Isotopes

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The neutron capture cross sections of $^{176}$Hf, $^{177}$Hf, $^{178}$Hf, $^{179}$Hf, $^{180}$Hf, and $^{175}$Lu, $^{176}$Lu have been measured in the energy range from 3 to 225 keV at the Karlsruhe 3.75 MV Van de Graaff accelerator. Neutrons were produced via the $^{7}$Li$(p,n)^{7}$Be reaction by bombarding metallic Li targets with a pulsed proton beam. The Karlsruhe $4\pi$ Barium Fluoride Detector was used for registration of capture events. The cross sections were determined relative to the gold standard using highly enriched oxide samples. The respective ratios could be obtained with overall uncertainties between 0.9 and 1.8%, about a factor of five more accurate than previous data. Partial cross sections to ground and isomeric states could be experimentally identified for neutron capture in $^{176,177,178,179}$Hf indicating a strong population of jet unknown isomeric states in $^{177}$Hf and $^{180}$Hf. This feature was further confirmed in extensive computer simulations with the GEANT code, using theoretically calculated capture cascades based of the known level schemes.

Maxwellian averaged neutron capture cross sections were calculated for thermal energies between $kT$ = 8 keV and 100 keV. Severe differences up to 40% were found to the data of a recent evaluation based on the existing experimental results. The new data allow for a much more reliable analysis of the important branching in the s-process synthesis path at $^{176}$Lu which can be interpreted as an s-process thermometer.

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## [487] Neutrons for science and industry — Uppsala neutron beam activities

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A wide programme on neutron-induced data for various applications is running at the 20–180 MeV neutron beam facility at the The Svedberg Laboratory, Uppsala. The main research areas are nuclear data for accelerator-driven transmutation of nuclear waste, single-event effects, and dose effects in fast neutron cancer therapy and aviation environments. In addition, experiments motivated by fundamental nuclear physics are undertaken. Moreover, commercial device testing motivated by single-event effects is a growing activity.

Two major experiment devices are frequently used; SCANDAL (SCAttered Nucleon Detection AssembLy), primarily intended for neutron elastic scattering, but also useful for (n,pX), (n,dX) and (n,n'X) reaction studies, and MEDLEY, aiming at studies of charged-particle production, ranging from protons to alpha particles.

The rapid growth in demand for neutrons has motivated the construction of a new neutron beam facility at TSL. The most important features of the new facility are:

- Increased intensity by reduction of the distance from neutron production to experiments.
- Availability of much larger beam diameters.
- Increased versatility concerning various beam parameters, like the shape.
- Reserved space for a future pulse sweeping system.

For nuclear data research, the increased intensity will facilitate a large experimental program at 180 MeV, hitherto excluded by count rate limitations.

For testing of electronics, the increased intensity in combination with a larger beam diameter, which facilitates testing of a large number of components simultaneously, will provide a total failure rate of about a factor 300 larger than for the present facility. This means that the new TSL neutron beam facility can outperform any existing facility in the world.

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## [526] GEANIE Measurements of Neutron-Induced Partial $\gamma$-ray Cross Sections for Nuclear Data

J. A. Becker

*LLNL, for the GEANIE Collaboration*

A wide variety of partial $\gamma$-ray cross sections produced in neutron-induced reactions in the energy range $1 < E_n < 200$ MeV have been measured over the past eight years. Reaction channel cross sections were deduced from these measurements with the aid of nuclear modeling. Enabling facilities are the intense "white" source of neutrons at the LANSCE/WNR 60R 20-meter flight path, and the precision $\gamma$-ray spectrometry of the Compton-suppressed Ge detector array GEANIE. Partial $\gamma$-ray cross sections are measured as a function of incident neutron energy using the time-of-flight technique. The first focus of the measurements was on the $^{239}$Pu(n,2n) cross section. This very successful experiment has been followed by a series of other experiments on nuclei throughout the periodic table. Representative measurements will be presented, along with the techniques we used. We will also present experiments in progress, as well as future plans.

Work performed under the auspices of the U.S. DoE by the University of California, Los Alamos National Laboratory (W-7405-ENG-36) and Lawrence Livermore National Laboratory (W-7405-ENG-48). Work benefitted from use of Los Alamos Neutron Science Center (W-7405-ENG-36).

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## [240] Neutron and Light Charged Particle Production in neutron or proton induced reaction on iron, lead and uranium at intermediate energy (20 to 200MeV) - The HINDAS collaboration

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In the framework of the european collaboration HINDAS (High and Intermediate energy Nuclear Data for Accelerator System), several experiments using european facilities (CYCLONE at Louvain-la-Neuve (Belgium), TSL at Uppsala (Sweden), AGOR at Groningen (Nederland)) were performed in order to obtain a complete set of data (see list below) at intermediate energy between 20 and 200 MeV. Double Differential Cross-Section for neutrons and light charged particles (proton to alpha particles) emitted in neutron or proton induced reaction on iron, lead and uranium are now avaible and will be presented after a brief description of the different facilities and associated set-up.

List of Experiment performed within the HINDAS collaboration : Fe, Pb, U (p,Xn+Ylcp) at 65 MeV - Fe, Pb, U (n,Xlcp) at 100 MeV - Fe, Pb, U (p,Xlcp) at 135 MeV

Using the Kalbach parametrization, differential cross-section in energy and production cross-section were derived from our measurements. Comparison with theoretical predictions will be shown in particular with existing codes as MCNPX, FLUKA, PREEQ but also with codes developped in the framework of the HINDAS collaboration as TALYS and DYWAN. While all differents approaches are in agreement with the measured neutron and proton production, none of them except PREEQ is able to reproduce complex particle emission. This result underline the strong need of new developments in theoretical prediction.

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## [154] First Measurements with a Lead Slowing Down Spectrometer at WNR

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The Lead Slowing Down Spectrometer (LSDS) recently installed at the Los Alamos Neutron Science Center (LANSCE) consists of a 1.2 meter cube of lead surrounding a tungsten target, which is bombarded by pulses of 800 MeV protons from the Proton Storage Ring (PSR). Neutrons are produced by spallation from the interaction of the proton pulse with the target. The aim of the LSDS is to keep the neutrons inside the lead volume for few hundreds of microseconds and to slow them down by small steps in energy before they leave the spectrometer. The advantage of the LSDS is the large amount of neutrons available in the lead volume compared to traditional time-of-flight experiments. Driving the LSDS with a pulsed proton beam increases the neutron flux per watt of beam power significantly over similar spectrometers driven by electron linear accelerators. With this flux, fission cross-section on very small samples (about tens of nanograms) can be studied. Our goal is the measurement of fission cross sections of highly radioactive nuclei including short-lived isomers. The characteristics of the LSDS (energy-time relation, energy resolution) are presented as well as the performance different detectors used for these measurements. These results are compared to MCNPX simulations. Results of initial measurements of fission and capture cross sections on microgram samples of actinides are presented in order to prepare the measurements with nanogram samples.

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# Nuclear Structure Evaluations

**Anasazi North**, Wednesday 10:30–12:10

[ 43] The Evaluated Gamma-ray Activation File (EGAF)
**R.B. Firestone [Invited]**

[500] Nuclear Structure Data for the Present Age
**C.M. Baglin [Invited]**

[ 86] K-Isomers as a Probe of Nuclear Structure and Advanced Applications
**F.G. Kondev [Invited]**

# Measurements of Cross Sections

**Anasazi South**, Wednesday 10:30–12:10

[327] Ternary Fission Induced by Polarised Neutrons
**F.J. Gönnenwein [Invited]**

[485] Nuclear Fission Research at IRMM
**F.-J. Hambsch [Invited]**

[231] Neutron-Induced Fission Cross Sections of $^{240}$Pu, $^{243}$Am and $^{nat}$W in the Energy Range 1 – 200 MeV
**A.B. Laptev**

[183] Thermal-Neutron-Induced Fission of $^{243}$Cm: Light-Peak Data from the Lohengrin Mass Separator
**I. Tsekhanovich**

# Astrophysics and Cosmology

**Sunset**, Wednesday 10:30–12:10

[510] Nuclear Physics Data Relevant to R-Process Nucleosynthesis
**K.-L. Kratz [Invited]**

[509] Neutron Reactions Relevant to S-Process Nucleosynthesis
**M. Heil [Invited]**

[224] Nuclear astrophysics at DANCE
**R. Reifarth**

[306] New Kr Cross Sections and Astrophysical Constraints on Presolar Grains
**P. Mutti**

## [43] The Evaluated Gamma-ray Activation File (EGAF)

Richard B. Firestone

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The Evaluated Gamma-ray Activation File (EGAF), a new database of prompt and delayed neutron capture gamma ray cross sections, has been prepared as part of an International Atomic Energy Agency (IAEA) Coordinated Research Project to develop a "Database of Prompt Gamma-rays from Slow Neutron Capture for Elemental Analysis". Recent elemental gamma ray cross-section measurements performed with the guided neutron beam at the Budapest Reactor have been combined with data from the literature to produce the EGAF database. EGAF contains thermal cross sections for ∼35,000 prompt and delayed gamma rays from 262 isotopes. New precise total thermal radiative cross sections have been derived for many isotopes from the primary and secondary gamma-ray cross sections and additional level scheme data. An IAEA TECDOC describing the EGAF evaluation and tabulating the most prominent gamma rays will be published in 2004. The TECDOC will include a CD-ROM containing the EGAF database in both ENSDF and tabular formats with an interactive viewer for searching and displaying the data. The Isotopes Project, Lawrence Berkeley National Laboratory continues to maintain and update the EGAF file. These data are available on the Internet from both the IAEA, National Nuclear Data Center, and Isotopes Project websites.

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## [500] Nuclear Structure Data for the Present Age

CORAL M. BAGLIN

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The US Nuclear Data Program maintains and provides easy and free access to several comprehensive databases that assist scientists to sift through and assess the vast quantity of published nuclear structure and decay data. These databases are an invaluable asset for nuclear-science experimentalists and theorists alike, and the recommended values provided for nuclear properties such as decay modes, level energies and lifetimes and radiation properties can also be of great importance to specialists in other fields such as medicine, geophysics, and reactor design. The Evaluated Nuclear Structure Data File (ENSDF) contains experimental nuclear structure data for all known nuclides, evaluated by the US nuclear data program evaluators in collaboration with a number of international data groups; the Nuclear Science Reference (NSR) database provides complementary bibliographic information; the Experimental Unevaluated Data Listing (XUNDL) exists to enable rapid access to experimental nuclear structure data compiled from the most recent publications (primarily in high-spin physics). This talk will present an overview of the nuclear structure and decay data available through these databases, with emphasis on recent and forthcoming additions to and presentations of the available material.

On behalf of the US Nuclear Data Program, funded by the US Department of Energy, Office of Science, Office of Nuclear Physics.

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## [86] K-Isomers as a Probe of Nuclear Structure and Advanced Applications

Filip G. Kondev

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A characteristic feature of deformed rare-earth nuclei in the region near A∼180 is the presence of long-lived, meta-stable states that are frequently called "K-Isomers". The long lifetimes arise from the large reorientation of the projection of the angular momentum on the symmetry axis (the K quantum number) with a simultaneous preservation of the axial symmetry.

Recent results from experiments aimed at studying exotic isomers at ATLAS, Argonne National Laboratory and at the Heavy Ion facility of the Australian National University will be presented. The emphasis will be on the structure of the isomers and their associated collective bands. The latter will be used to reveal some interesting nuclear structure effects, such as the interplay between collective motion (involving the whole nucleus) and individual nucleon dynamics, and the step-wise collapse of the pairing correlations in nuclei. Results on similar K-isomers in A∼130 nuclei will be also outlined.

These nuclei are less deformed and more susceptible to shape changes, shape co-existence and triaxiality than the well-deformed cases known in the A∼180 region. Such differences will affect both the decay transition strengths (and therefore lifetimes) and also the likelihood of isomers occurring in the odd-A nuclei since their properties may change significantly due to effects from the odd particle. Finally, a possible application of the $T_{1/2}$=31 yr, $K^{\pi}=16^{+}$ isomer in $^{178}$Hf and the $T_{1/2}$=160 d, $K^{\pi}=23/2^{-}$ isomer in $^{177}$Lu as a simulated energy release device, as well as the astrophysical relevance of long-lived isomers in $^{180}$Ta and $^{176}$Lu, will be also discussed.

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## [327] Ternary fission induced by polarised neutrons

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Both, for binary and ternary fission, parity conserving and parity non- conserving angular distributions of fission fragments have been studied in the last years. The experimental technique is based on the use of polarised cold neutrons in (n,f) fission reactions. From a comparison of the angular anisotropies of fragments for the two above modes of fission decay it can e.g. be learned when in the process the ternary light charged particles are formed. More recently, for ternary fission also triple correlations between the spin of the neutron inducing fission and the two momenta of the light fision fragment and the light charged particle have been investigated. Surprisingly, sizable correlations were discovered for the two fissile U-isotopes $^{233}$U and $^{235}$U. By contrast, in very recent experiments no such correlation could be disclosed for $^{239}$Pu(n,f)as the target.

While the theory of the angular anisotropies under discussion is well established, the newly discovered triple correlation has not yet found a generally accepted interpretation. Several models have been proposed. An appealing suggestion is that, upon ejection of a ternary particle from the neck of a fissioning nucleus which is rotating, the Coriolis force will bring about the correlation observed. The size of the correlation should hence depend on the spin of the compound nucleus which is larger for the U-isotopes (2 to 4 Planck units) than for the Pu-isotope studied (0 or 1 Planck units). The smaller size of the effect being expected for $^{239}$Pu could be the reason why the correlation has escaped detection in experiment.

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## [485] Nuclear Fission Research at IRMM

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The Institute for Reference Materials and Measurements (IRMM) will celebrate its 45$^{\text{th}}$ anniversary in 2005. With its 150 MeV Geel Electron Linear Accelerator (GELINA) and 7 MV Van de Graaff accelerator, it served the neutron community for this period.

The research in the field of Nuclear Fission was focused in recent years on both the measurement and calculation of fission cross-sections, and the measurement of fission fragment properties.

Fission cross-sections were measured for $^{233}$Pa, $^{234,236}$U, the fission process was studied for $^{239}\text{Pu}(n,f)$ in resonances, $^{251}\text{Cf}(n_{\text{th}},f)$. These measurements derive their interest from accelerator driven systems, the thorium cycle, high temperature reactors, safety of current reactors and basic physics. The measurements are supported by several modelling efforts that aim at improvement of data evaluation.

Some of the highlights will be presented together with an outlook on future activities.

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## [231] Neutron-induced fission cross sections of $^{240}$Pu, $^{243}$Am and $^{nat}$W in the energy range 1 - 200 MeV

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The neutron-induced fission cross section of $^{240}$Pu, $^{243}$Am and $^{nat}$W have been measured in the wide energy range of incident neutrons from 1 MeV to 200 MeV as the next stage of fission cross section investigation program performed at the GNEIS facility [1] in frame of ISTC Project # 1971. During the previous stage of this research program the measurement of fission cross-sections of $^{233}$U, $^{238}$U, $^{232}$Th, $^{237}$Np, $^{239}$Pu, $^{nat}$Pb and $^{209}$Bi have been performed under support of ISTC grant # 609-97 [2]. The measurements are performing simultaneously for each investigated isotopic targets using multiplate ionization chamber and time-of-flight technique on a 48-m flight path. The 1-GeV proton synchrocyclotron of PNPI was used as a "white spectrum" neutron source with average intensity $3{\cdot}10^{14}$ n/s, burst duration 10 ns and repetition rate up to 50 Hz. TOF and pulse-height spectra were measured and accumulated for each target using the data acquisition system based on a 100-MHz FLASH-ADC. Statistical accuracy of measured cross section of actinide nuclei $^{240}$Pu and $^{243}$Am is about 2 % at neutron energies above fission threshold and that of sub-actinide nucleus $^{nat}$W is about 10 %. The experimental data obtained are presented in comparison with the data of other authors and theoretical calculations based on a Hauser-Feshbach statistical model. The first result of this measurement has been presented earlier [3,4].

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## [183] Thermal-Neutron-Induced Fission of $^{243}$Cm: Light-Peak Data from the Lohengrin Mass Separator

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The mass separator Lohengrin, at the Institut Laue-Langevin in Grenoble (France), was used to measure yields and kinetic energies of light fission products with masses from $A$=72 to $A$=122 from the fission of the $^{244}$Cm$^*$ compound nucleus, induced by thermal neutrons. The use of an ionisation chamber as a detection device, in the $\triangle E - E$ mode, allowed also the isotopic yields to be determined for the very-light masses measured (up to $A$=90).

The fission-fragments' kinetic energy was found to remain practically constant for all masses starting from the very light ones and up to approximately the onset of the mass-yield descent towards the symmetry region. There, the kinetic energy shows a sharp fall, resulting in a strong change of its value within

only a few mass numbers. These observations are in accordance with systematics on the kinetic-energy behaviour known from the fission of other compound nuclei.

A comparison has been made of the results obtained on the mass yields with those from the fission $^{245}$Cm as well as with the data given by the $JEF-2.2$ and $ENDF/B-VI$ libraries. The presence of two additional neutrons in the $^{246}$Cm$^*$ compound nucleus manifests itself only for the masses on the right wing of the peak (more symmetric mass splits), as a difference in the mass yields. For more lighter masses, the two experimental data sets practically coincide. Among the libraries, the $ENDF/B-VI$ data were found to agree best with the experimental results, with the exception for a very few masses in the super-asymmetric ($A$ <80) and truly-symmetric ($\sim A$=120) mass regions.

Finally, a comparison encompassing all experimental data on mass yields measured so far on the Lohengrin mass separator is made for fission of different compound nuclei. The intersection of different mass-yield curves in the super-asymmetric mass region is pointed out, emphasising the stabilising role of the $Z$=28 and $N$=50 shells in the light fragments, throughout a variety of nuclei undergoing fission.

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## [510] Nuclear Physics Data Relevant to R-Process Nucleosynthesis

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The production of about half of the heavy elements in nature occurs via the r-process, i.e. a combination of rapid neutron captures, the inverse photodisintegrations, and slower $\beta$-decays, $\beta$-delayed processes as well as fission and possibly interactions with neutrino fluxes. A correct understanding and modelling of this nucleosynthesis process requires the knowledge of nuclear properties far from stability [1,2] and a detailed description of the astrophysical environments. Experiments at radioactive ion beam facilities have played a pioneering role in exploring the characteristics of nuclear structure in terms of masses and $\beta$-decay properties. Initial examinations paid attention to short-lived "waiting-point nuclei with magic neutron numbers related to the location and height of the solar-system r-process abundance peaks, while more recent activities, mainly in the $^{132}$Sn region, focus on the evolution of shell effects as a function of isospin. In this context, shape transitions and the erosion of the classical shell gaps with possible occurrence of new magic numbers play an important role [3,4].

Consequences of the improved nuclear data input on calculations of the r matter flow up to the A$\sim$260 fission region will be presented for realistic astrophysical scenarios, and the applicability of the long-lived actinides $^{232}$Th and $^{238}$U as cosmochronometers will be discussed [5,6].

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## [509] Neutron reactions relevant to s-process nucleosynthesis

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The last decades have seen an enormous progress in modelling astrophysical object which lead to a significantly improved understanding of various nucleosynthesis scenarios. This applies in particular for asymptotic giant branch (AGB) stars where about half of the heavy elements are synthesised by the main component of the s process. In order to test these models and to compare the model predictions with observational data accurate neutron capture cross sections of isotopes with mass numbers $A > 90$ are indispensable. This holds especially for nuclei near closed neutron shells and in the vicinity of branch points since the analysis of s-process branchings yields important information on stellar parameters like temperature, neutron densities, mass densities and even convection time scales during the s process. Within this picture neutron reactions on abundant light elements are also important since these act as neutron poisons, hence affecting the neutron balance in the star. Finally, also the most important neutron sources for the s process, $^{13}$C($\alpha$,n)$^{16}$O and $^{22}$Ne($\alpha$,n)$^{25}$Mg, will be discussed.

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## [224] Nuclear astrophysics at DANCE

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One of the most interesting nuclear physics challenges is obtaining a detailed understanding of the nucleosynthesis processes of the elements. Knowledge about the stellar sites, and how they are governed by stellar evolution and cosmology are a crucial in understanding the overall picture. Information on reaction rates for neutron and charged-particle induced reactions have a direct impact on existing stellar models. Except for the stable isotopes, very few neutron-induced reactions in the energy range of interest have been measured to date. DANCE measurements on unstable isotopes will provide many of the missing key reactions that are needed to understand the nucleosynthesis of the heavy elements. Recent measurements at DANCE motivated by nuclear astrophysics will be presented and possibilities for future experiments will be outlined.

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## [306] New Kr Cross Sections and Astrophysical Constraints on Presolar Grains

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Isotopes between Fe and Sr are mainly synthesized by the so-called weak s-process component through the activation in massive stars of the $^{22}$Ne($\alpha$,n)$^{25}$Mg neutron source during core-He or shell C-burning evolutionary phases. Their abundances are also partially contributed by the main s-process component, which is responsible for the production of heavier elements from Y up to Pb. This component has been associated to shell He-burning during the AGB evolutionary phase in low mass carbon stars. According to the most recent double pulse s-process model the neutron exposure per pulse, which determines the overall s-process efficiency, is built by the $^{13}$C($\alpha$,n) neutron source, while a minor burst of neutrons driven by the $^{22}$Ne($\alpha$,n) reaction, involving higher neutron density, largely modifies the final isotopic distribution of reaction-branching dependent nuclides. The measured large spread in the in the ratio $^{86}$Kr/$^{82}$Kr found in silicon carbide (SiC) grains of different size is an indirect confirmation of the double pulsed nature of the s-process in carbon stars. Indeed, the marginal activation of the $^{22}$Ne neutron

source produces a relatively short (in time) but intense neutron burst of high peak neutron density. In these conditions the neutron-rich channel at $^{85}$Kr branching in the s-process path is partially open providing the necessary $^{86}$Kr abundance. This branching is of great interest because can deliver essential information on the neutron flux in the specific stellar site. With the aim to improve the knowledge of the neutron capture cross section of the principal Krypton isotopes and therefore to reduce the uncertainties on the s-process models, the neutron capture cross section of $^{82}$Kr, $^{84}$Kr and $^{86}$Kr, on both resolved and unresolved resonance regions, have been measured with high resolution at the GELINA facility in Geel. The Maxwellian-averaged capture cross section versus stellar temperature has been calculated. In addition, a partial analysis of $^{80}$Kr and $^{83}$Kr resonances in a limited energy range has been also carried out.

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# Applications: Fusion

**Anasazi North**, Wednesday 13:30–15:10

[333] Nuclear Data for Fusion Energy Technologies: Requests, Status and Development Needs
**U. Fischer [Invited]**

[533] Radiochemical Diagnostics for National Ignition Facility Ignition Capsules
**P. Bradley [Invited]**

[275] The European Activation File, EAF-2005
**R.A. Forrest**

[239] Measurement of Neutron Reaction Cross Sections between 8 and 14 MeV
**W. Mannhart**

# Measurements of Cross Sections

**Anasazi South**, Wednesday 13:30–15:10

[369] Neutron TOF and Ion Beam Irradiation Apparatus in Ten's of MeV Region at Tohoku University Cyclotron Laboratory
**M. Baba [Invited]**

[ 32] Reaction Cross Sections for Protons on Targets from $^{12}$C to $^{208}$Pb at Incident Energies Between 80 and 200 MeV
**M. Lantz**

[117] Elastic Neutron Scattering at 96 MeV
**A. Hildebrand**

[184] Residual Nuclide Production from Iron, Lead, and Uranium by Neutron-Induced Reactions up to 180 MeV
**R. Michel**

# Nuclear Structure Evaluations

**Sunset**, Wednesday 13:30–15:10

[512] Nuclear Decay Data: On-going Studies to Address and Improve Radionuclide Decay Characteristics
**A.L. Nichols [Invited]**

[504] Progress in Nuclear Masses
**G. Audi [Invited]**

[301] Accurate Determination of Neutron Binding Energies
**M. Jentschel**

[415] shape Coexistence at the Outer Edges of Stability
**M.P. Carpenter**

## [333] Nuclear Data for Fusion Energy Technologies: Requests, Status and Development Needs

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The worldwide efforts in fusion energy technology aim at developing, on the long-term, power reactors which can contribute substantially to the supply of electricity. The construction and operation of the experimental fusion device ITER ("International Thermonuclear Experimental Reactor") and the intense neutron source facility IFMIF ("International Fusion Material Irradiation Facility") are considered as important next steps towards this long-term goal. The layout and development of these facilities and their nuclear components relies to a large extent on data provided by neutronics design calculations. The availability of qualified computational tools and nuclear data for the neutron transport simulation and the calculation of relevant nuclear responses is thus a prerequisite to enable reliable design calculations for these facilities. Related international efforts currently focus on the development of qualified nuclear data to serve the specific needs of the ITER and the IFMIF projects.

The paper provides a brief outline of the current fusion technology long-term strategy with the near term focus on ITER and IFMIF and presents an overview of the nuclear data required for related design calculations. The status of the available nuclear data is reviewed and future development needs are identified with regard to nuclear data for neutron and photon transport, radiation damage, sensitivity/uncertainty and activation/transmutation calculations.

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## [533] Radiochemical Diagnostics for National Ignition Facility Ignition Capsules

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In 2010 (or shortly thereafter), the National Ignition Facility (NIF) is scheduled to achieve ignition. We propose radiochemistry of the burn products as an attractive way to measure the amount of DT fuel that is mixed in with the surrounding ablator material. In addition, radiochemistry offers the possibility to measure the temperature history of the DT fuel burn, the $\langle \rho r \rangle$, and the neutron fluence of reaction-in-flight, 14 MeV, and low energy neutrons. We can use prompt $\beta$ spectroscopy from the debris products and collection of the debris (for mass spectroscopy) to make the radiochemical measurements. Radiochemistry thus offers the opportunity to make unique measurements as well as provide cross checks with results from other diagnostics for NIF ignition capsules. We will mostly discuss reactions involving 0.9 atom % copper doped beryllium ablator capsules, but we will also look at Ge-doped plastic ablators and different hohlraum materials.

This work performed under the auspices of the U.S. Department of Energy by Los Alamos National Laboratory under Contract W-7405-ENG-36.
LA-UR-04-6090

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## [275] The European Activation File, EAF-2005

Robin A. Forrest

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The current version of the European Activation File is EAF-2003. This library contains various libraries of nuclear data required for activation calculations. An important component is the neutron-induced cross section library. This contains cross section data for 12,617 reactions with an upper limit of 20 MeV. Plans to expose fusion components to high neutron fluxes include the IFMIF materials testing facility. This accelerator-based device will produce neutrons with a high-energy tail up to about 55 MeV. In order to carry out activation calculations on materials exposed to such neutrons it is necessary to extend the energy range of the cross section library.

Work on extending the energy range to 60 MeV is nearing completion. A test version (EAF-2004) was produced at the end of 2003 showing the feasibility of the chosen approach. This library required calculated data to extend the existing data from 20 - 60 MeV and to enlarge it with new classes of reaction with high thresholds. It contained 62,860 reactions and was based on results from the TALYS model code. Results of the testing of EAF-2004 and its improvement based on new data sources, experimental differential and integral data are reported. A summary of the new library EAF-2005, which is under development and is planned for distribution at the beginning of 2005, is given.

The other files in EAF-2005 are briefly described, these cover cross section uncertainty information and decay data, Both these have been extended beyond the current version to allow activation calculations at energies up to 60 MeV.

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## [239] Measurement of Neutron Reaction Cross Sections between 8 and 14 MeV

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Cross section measurements were performed with special emphasis on access to the "blind spot" in the neutron energy range between 10 and 13 MeV. The use of a conventional D(d,n) neutron source in combination with detailed TOF measurements of the D(d,np) breakup component, necessary to take the non-monoenergetic contributions into account, allows the precise determination of monoenergetic cross section data. The energy scale of the experiment bases on time-of-flight measurements of the neutrons and yields final uncertainties of 20 keV.

The present measurement comprises cross section data of Zn-64(n,p)Cu-64, Zn-64(n,2n)Zn-63, Cu-63(n,2n)Cu-62 and Cu-65(n,2n)Cu-64. The measurement of the Zn-64(n,p)Cu-64 reaction is the only experiment which completely covers the shape of this cross section between 8 and 14 MeV. The high accuracy of the neutron energy scale allowed the determination of precise cross section data near threshold of the (n,2n) reactions. The reaction products of all of the investigated reactions were strong positron emitters. The radioactivty counting technique has been optimized to guarantee complete annihilation and considers counting losses due to annihilation in flight.

The uncertainties of the data are between 2.5% and 4%. The cross section data of the present work are compared with data of other experiments and of available evaluations.

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## [369] Neutron TOF and ion beam irradiation apparatus in ten's of MeV region at Tohoku University cyclotron laboratory

Mamoru Baba, Masayuki Hagiwara, Takao Aoki, Naoki Kawata, Atsuki Terakawa, Hikonojyo Orihara, Tsutomu Ohtsuki

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Data on neutron production and radio nuclide-production are of prime importance for accelerator application and the space technology.

In the Cyclotron and Radioisotope Center, Tohoku University (CYRIC), equipped are an AVF cyclotron (K=110 MeV) and 1) a neutron TOF system employing a beam swinger and a well-collimated neuron flight path up to 44 m, and 2) an automated irradiation/ sample changing mechanism. For 1), a beam chopper to reduce the beam frequency to 1/10 is also available to enable TOF measurements down to $< 1$ MeV.

The beam swinger TOF system enables measurement of angular distributions without changing the detector arrangement from 0-deg. to 145-deg (now up to 110-deg). A bending magnet is employed to sweep out the beam which have transmitted the target into a beam dump. Therefore, measurement at 0-deg is possible for thin targets. Using the system, measurements have been done on energy-angular differential thick targets neutron yields for (p,n) and (d,n) reactions, and neutron emission cross section for thin targets at ten's of MeV region. Experiment will be extended to thin targets of major elements.

The irradiation system consists of irradiation chamber, cooling system, sample transporter and a beam collimator. Samples are kept in the chamber and set on the transporter outside the room. It is transported to the target position and set at irradiation position, irradiated and returned according to the program. This is used for activation cross sections and/or radionuclide production by the ion beam bombardment. By applying the stacked target technique, excitation functions are being obtained for

proton and deuterons. Activation by neutrons are also in progress using quasi-monoenergetic neutrons produced by the $^{7}$Li(p,n) reactions.

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## [32] Reaction cross sections for protons on targets from $^{12}$C to $^{208}$Pb at incident energies between 80 and 200 MeV

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Experimental reaction cross sections of proton scattering from nuclei are implicitly of fundamental importance for our understanding of proton-induced reaction mechanisms, which in turn nowadays find application in chemistry, medicine and astrophysics. These applications are the motivation for the determination of global nucleon optical models which are used to calculate distorted waves in theories that, at any energy, predict scattering and nuclear reactions in the irradiated medium. These global potentials are derived from the vast set of existing experimental data comprising differential cross section angular distributions, polarizations, asymmetries and spin-rotation parameters. However, the derived potentials are not unique and manifest ambiguities. In some cases two potentials can predict almost identical angular distributions and still predict quite different values of the reaction cross section. The reason why reaction cross sections have found limited use as a constraint in the derivation of the global potentials, is the fact that existing data are much less accurate than the data for angular distributions. Furthermore, apart from the lack of reaction cross section data on some important target nuclei, existing experimental data often manifest serious inconsistencies.

Results of new reaction cross section measurements on $^{12}$C, $^{40}$Ca, $^{90}$Zr and $^{208}$Pb at incident proton energies in the important range of 80 to 200 MeV will be presented. The accuracy of the new data compared to existing measurements will be discussed.

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## [117] Elastic neutron scattering at 96 MeV

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A facility for detection of scattered neutrons in the energy interval 50-130 MeV, SCANDAL (SCAttered Nucleon Detection AssembLy), has recently been installed at the 20-180 MeV neutron beam line of the The Svedberg Laboratory, Uppsala. Elastic neutron scattering from $^{12}$C, $^{56}$Fe, $^{89}$Y and $^{208}$Pb has been studied at 96 MeV in the 10-70° interval. The results from $^{12}$C and $^{208}$Pb have recently been published, while the data from $^{56}$Fe and $^{89}$Y are under analysis and will be presented at the conference. The achieved energy resolution, 3.7 MeV, is about an order of magnitude better than for any previous experiment above 65 MeV incident energy. The present experiment represents the highest neutron energy where the ground state has been resolved from the first excited state in neutron scattering. A novel method for normalization of the absolute scale of the cross section has been used. The estimated normalization uncertainty, 3 %, is unprecedented for a high-energy neutron-induced differential cross section

measurement on a nuclear target. The results are compared with modern optical model predictions, based on phenomenology or microscopic nuclear theory. Applications for these measurements are within nuclear waste incineration, single event upsets in electronics and fast-neutron cancer therapy.

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## [184] Residual nuclide production from iron, lead, and uranium by neutron-induced reactions up to 180 MeV

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Within the HINDAS project, activation experiments with quasi mono-energetic neutrons were performed at the neutron beam lines at The Svedberg Laboratory (TSL), University Uppsala / Sweden and the Universite Catholique de Louvain La Neuve (UCL) / Belgium in order to determine excitation functions for the production of residual radionuclides from a variety of target elements. A total of 10 activation experiments covered proton energies between 36.4 MeV and 178.8 MeV. Residual radionuclides with half-lives between 20 min and 5 years were measured by off-line $\gamma$-spectrometry.

At UCL, the absolute neutron fluence was determined with three methods: a proton recoil telescope, a $^{238}$U fission ionization chamber, and an NE213 liquid scintillation detector. The spectral fluence was measured with the TOF method, employed with the latter two systems. At TSL, measurements of the neutron peak fluences inside the target stack were carried out by thin-film breakdown counters.

Information on the energy dependence of the neutron spectra in the targets was obtained by modeling the neutron spectra by Monte Carlo techniques using the LAHET/MCNP code system. These transport calculations started either from the experimentally determined neutron spectra (at UCL) or from the systematic of experimentally measured neutron emission spectra of the Li-7(p,n)-reaction. The calculations described the transport of the neutrons into the target stacks and into the individual targets as well the production and transport of secondary particles inside the massive target stacks which cannot be neglected.

Cross sections cannot be directly calculated from these response integrals since the neutrons used are just "quasi mono-energetic" with only about 30 to 50% of the neutrons in the high-energy peak with a width of a few MeV. The neutron cross sections were extracted from production rates determined in a series of irradiation experiments with different neutron energies by unfolding using the STAYS'L formalism starting from guess functions calculated by the ALIPPE code. Here, we report and discuss the results for the target elements Fe, Pb, and U and discuss them in the context of theoretical predictions using the TALYS code.

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## [512] Nuclear Decay Data: On-going Studies to Address and Improve Radionuclide Decay Characteristics

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Decay data activities throughout the nuclear-data community are somewhat diverse and sparse compared with the amount of effort focused historically on improving our knowledge of the important cross sections identified with various fission and fusion processes. However, there are decay parameters for a

significant number of radionuclides that require more accurate and reliable characterization in order to achieve the desired credibility when addressing safety criteria and cost-effective demands for: decay-heat assessments; shielding requirements for irradiated nuclear fuel; both the intermediate- and long-term treatment and storage of radioactive waste; activation of structural materials and impurities within fusion devices; and non-energy related applications, such as diagnostic studies and therapeutic treatments in nuclear medicine, and standards for various nuclear-based analytical techniques.

Known decay data studies are described, ranging from various measurement programmes to the maintenance of evaluated decay-data libraries. Gross beta-decay measurements are essential to address the decay-data requirements for short-lived fission products, well-defined half-lives are required in assessments of the storage of long-lived radionuclides in waste depositories, and improved decay data continue to be demanded in safeguards, to improve detector-calibration standards, and for medical and analytical applications. Such needs require the measurement of good quality decay data, along with the multinational formulation and undertaking of decay-scheme evaluations through agreed procedures.

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## [504] Progress in Nuclear Masses

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Different types of experimental data require different procedures for collection and for evaluation. In nuclear physics in particular, we might be interested in data on nuclear levels, their energies, their gamma decays. These data are collected and evaluated "vertically" in a network worldwide (ENSDF). I am more directly concerned with the evaluation of the masses of nuclei, more precisely their atomic masses, in what we call the Atomic Mass Evaluation (AME). And also, directly connected to the masses, by the properties of ground-states and long-lived isomers of nuclei, their spins, half-lives, excitation energies and decay modes, called the NUBASE evaluation. Masses as well as nuclear and decay properties have in common to require "horizontal" collection and evaluation.

After developing some general ideas about evaluations and explaining the various concepts above, I will describe the most prominent features of the AME, the reasons for its complexity, how they are faced and solved. I will explain why it was found essential to create the NUBASE evaluation and how we finally succeeded in having AME and NUBASE co-ordinated and finally published for the first time together last December.

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## [301] Accurate determination of neutron binding energies

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The combination of high precision gamma ray measurements with precison mass determinations allows to determine fundamental constants, like the neutron mass and the molar Planck constant. The basic principle of these measurements will be discussed. Experimental results from measurements with $^{29}$Si, $^{36}$Cl, $^{33}$S and $^{49}$Ti will be presented. Further progress in the precision of the mass measurements is stimulating a new generation of binding energy measurements. The basic concept for these measurements will be reviewed.

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# [415] SHAPE COEXISTENCE AT THE OUTER EDGES OF STABILITY

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Above N=82, the proton dripline follows closely the outer edge of the well deformed rare-earth region, and the ground states of nuclei lying close to the dripline are expected to have spherical or weakly deformed prolate shapes. Our recent experimental studies have concentrated in the upper portion of this region, namely the study of excited states in Os (Z=76) through Pb (Z=82) isotopes located in the vicinity of the proton dripline. One of our principle motivations has been to characterize the evolution of shape from the well studied deformed region to the near spherical ground states deduced for the proton emitters [1].

In-beam $\gamma$-ray studies of such heavy systems far from stability are hampered by the large fission cross sections associated with the heavy-ion fusion reactions which are used to produce these proton-rich nuclides. However, the use of recoil separators allows one to easily distinguish fusion-evaporation residues from fission products. In addition, all nuclides in this region which lie at the dripline or beyond, decay via charge particle radioactivity. As a result, the recoil decay tagging (RDT) technique can be utilized allowing for in-beam $\gamma$-ray studies of nuclides produced with sub-$\mu$b cross-sections. By coupling the Fragment Mass Analyzer (FMA) with Gammasphere, the high-spin structure of a number of nuclides in this Os-Pb region has been investigated. In addition, complimentary decay studies of these same nuclides have allowed, in several instances, spin/parity and excitation energy assignments for all observed states. These studies have allowed us to characterize the evolution of nuclear shapes as one approaches the proton drip line. In several isotopes, structures built on three distinct shapes at low excitation energy have been observed [2,3].

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# Processing, Testing, and Validation of Evaluated Data

**Anasazi North**, Wednesday 15:30–17:30

[ 70] Consistency Testing of the IRDF-2002 Dosimetry Cross Section Library
**P.J. Griffin**

[ 85] Comparison of Results from the MCNP Criticality Validation Suite Using ENDF/B-VI and Preliminary ENDF/B-VII Nuclear Data
**R.D. Mosteller**

[250] Validation of MA Nuclear Data by Sample Irradiation Experiments with the Fast Reactor JOYO
**S. Ohki**

[267] Benchmarking of Uranium-238 Evaluations Against Spherical Transmission and (n,xn)-Reaction Experimental Data
**S.P. Simakov**

[348] Comparison of Ramsauer and Optical Model Neutron Angular Distributions
**D.P. McNabb**

[ 37] Scaling Relations for the Hard Component of Light Hadron Scattering Spectra
**R.J. Peterson**

# Standards

**Anasazi South**, Wednesday 15:30–17:30

[145] Status of the International Neutron Cross Section Standards File
**V. Pronyaev [Invited]**

[496] Measurement of the Absolute np Scattering Differential Cross Section with a Tagged Neutron Beam at Intermediate Energies
**S.E. Vigdor [Invited]**

[111] Forward-Angle np Scattering at 96 MeV and Normalization of Neutron-Induced Nuclear Reactions
**C. Johansson**

[207] Particle Leaking, Cross-Sections Ratio $^{10}$B(n,$\alpha$)/$^{238}$U(n,fission), and Excitation Function of the Reaction $^{10}$B(n,$\alpha$)$^{7}$Li at MeV Energies
**G. Giorginis**

[372] New Results for the $^{6}$Li and $^{10}$B Neutron Standard Cross Sections from R-matrix Analyses and Microscopic Calculations for the $^{7}$Li and $^{11}$B Systems
**G.M. Hale**

# Nuclear Data Evaluations

**Sunset**, Wednesday 15:30–17:30

[545] Recent Cross Section Evaluations in the Resonance Region at the Oak Ridge National Laboratory
**L.L. Leal [Invited]**

[153] Systematic Analysis of Uranium Isotopes
**P.G. Young [Invited]**

[ 77] Multiplicities and Spectra of Prompt Fission Neutrons up to 200 MeV
**V. Maslov**

[221] Direct-Semidirect Neutron Capture Calculations Applied to R-Matrix Data Evaluations in the Resolved Resonance Region
**G. Arbanas**

[ 95] Calculations of Neutron and Proton Induced Reaction up to 200 MeV for Target $^{238}$U
**H. Yu**

## [70] Consistency Testing of the IRDF-2002 Dosimetry Cross Section Library

Patrick J. Griffin

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The new IRDF-2002 dosimetry cross section library is due to be released by the IAEA in January 2004. An important aspect of the new library development and release process was the "consistency" testing of these cross sections in "reference" neutron fields. This paper reports on and quantifies the degree of consistency in the testing.

Uncertainties addressed in the C/E integral metrics include: experimental activity measurements, characterization of the neutron reference field spectra, and uncertainty in the evaluated dosimetry cross section. One major limitation encountered in gathering activation data from reference neutron fields was the difficulty in obtaining uncertainties and covariance matrices for the neutron spectra in the reference fields. The Sandia Pulsed Reactor (SPR-III) and the Annular Core Research reactor (ACRR) were two reference benchmark neutron fields used to support the testing. The IRDF-2002 library consists of 65 different reactions. Thirty one of these reactions were addressed and found to be consistent with each other in these two neutron fields. Experimental activities were not available for 26 other reactions. Six of the remaining reactions are partial cross sections that are addressed in composite form in other library entries. The two remaining cases are reactions where either the short half lives or self shielding considerations have resulted in requests that additional experimental data be gathered in the fields.

Data in the reference fields were gathered for reactions using bare foils as well as cadmium and enriched $^{10}$B boron carbide covers. For several reactions, the bare and boron-covered C/E ratios were fine, but the cadmium-covered reaction had C/E values that were off by more than two standard deviations. Inspection of the C/E ratios for the covered foils identified what is thought to be problems with the $^{nat}$Cd absorption cross sections just above the Cd cut-off energy. The absence of any uncertainty data for the cadmium absorption cross section and the sparse data for cadmium absorption cross sections seen in the ENSDF database leads to questions about the quality of the cadmium cross sections in the resonance region.

This cross section consistency testing 1) demonstrates to users of the IRDF-2002 library which reactions have been validated so that they can evaluate any discrepancies that they observe when using these dosimetry cross sections for spectrum determinations purposes; 2) identifies needs for additional dosimetry data in reference neutron fields; 3) identified problems in the cadmium cross sections.

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## [85] Comparison of Results from the MCNP Criticality Validation Suite Using ENDF/B-VI and Preliminary ENDF/B-VII Nuclear Data

Russell D. Mosteller

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*[LA-UR-03-8855]* The MCNP Criticality Validation Suite is a collection of 31 benchmarks taken from the International Handbook of Evaluated Criticality Benchmark Experiments. It includes cases with a variety of fuels, moderators, reflectors, spectra, and geometries. Specifically, it contains six cases with U-233 fuel, eight cases with highly enriched uranium (HEU), six cases with intermediate-enriched uranium (IEU), two cases with low-enriched uranium (LEU), and nine cases with plutonium. Except for LEU (which can reach criticality only with a thermal spectrum), there are cases with fast, intermediate, and thermal spectra for each of these fuels. The fast cases include bare spheres, cores with heavy reflectors, cores with light reflectors, and lattices. The thermal cases include lattices of fuel pins and solutions for each of the five types of fuel. The cases with intermediate spectra are less uniform, due to the limited number of experiments with such spectra.

Three sets of MCNP5 calculations were performed for the MCNP Criticality Validation Suite. The first set employed nuclear data from ENDF/B-VI Release 8, the final release for ENDF/B-VI. The second set employed preliminary ENDF/B-VII data generated by group T-16 at Los Alamos National Laboratory for the uranium isotopes and for plutonium-239 but retained ENDF/B-VI data for all other nuclides. The third set was the same as the second except that a new set of U-238 resonance parameters generated by researchers at Oak Ridge National Laboratory (ORNL) was added to the T-16 evaluation.

All cases were run with 250 generations of 5,000 neutrons each. Results from the first 50 generations of each case were omitted from the statistics. Consequently, the results from each case are based on a total of 1,000,000 active neutron histories.

The preliminary ENDF/B-VII data produce marked improvements in k-eff for bare spheres of U-233 (Jezebel-233), HEU (Godiva), and plutonium (Jezebel). Furthermore, the reactivity swings between those cases and the corresponding Flattop cases (which enclose the sphere inside an annulus of normal

uranium) are substantially decreased. They also significantly improve k-eff for BIG TEN (IEU reflected by normal uranium) and for HEU and plutonium spheres immersed in water. In addition, inclusion of the ORNL resonance parameters for U-238 produces a significantly better value for k-eff for the lattice of LEU fuel pins in water.

At the same time, they produce worse results than ENDF/B-VI for thermal lattices of U-233 and HEU pins, for an IEU sphere reflected by graphite, and for a plutonium sphere reflected by thorium (THOR). Furthermore, k-eff for the uranium cases with intermediate spectra remains substantially underpredicted, while k-eff for the plutonium case with an intermediate spectrum (HISS/HPG) continues to be significantly overpredicted.

In conclusion, preliminary ENDF/B-VII evaluations for the uranium isotopes and Pu-239 appear to produce substantial improvements for certain cases with fast spectra and for lattices of LEU fuel pins in water. However, improvements still are needed in some areas, particularly those cases with intermediate spectra.

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## [250] Validation of MA nuclear data by sample irradiation experiments with the fast reactor JOYO

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Japan Nuclear Cycle Development Institute is developing a commercialized fast reactor cycle system which involves the recycling of minor actinide (MA) nuclides. To develop a burnup calculation method and to validate MA nuclear data, we have launched the isotopic composition analysis of MA samples ($^{237}$Np, $^{241}$Am, $^{243}$Am, $^{244}$Cm) irradiated at the experimental fast reactor JOYO. The irradiation was performed for 200-250 EFPD during the period of 1994 to 1999. Post irradiation examination (PIE) of the first sample (one of $^{243}$Am samples) was finished in October, 2003.

The preliminary analysis on the $^{243}$Am sample has been performed. The sample was initially composed of 12.2% of $^{241}$Am and 87.8% of $^{243}$Am. We focused on the creation of $^{242m}$Am from $^{241}$Am, as well as that of $^{244}$Cm from $^{243}$Am. Main purpose of the former one was to validate the isomeric ratio (IR) of $^{241}$Am capture reaction. There exist only two IR evaluations with following large discrepancy: about 0.8 (ground/(ground + meta)) given from ENDF/B-VI under fast reactor spectrum, while about 0.7 from JENDL-3.3. This discrepancy influenced strongly on the creation amount of $^{242m}$Am. Assuming IR = 0.8 and using JENDL-3.2, we obtained the preliminary C/E value of 1.30 for the abundance ratio of $^{242m}$Am/$^{241}$Am. In the case of IR = 0.85, the C/E value reduced to 1.00. To use other nuclear data libraries (IR was set to 0.85) did not change the C/E value considerably. The experimental error was about 2% via mass spectroscopy, which was small enough. The above results implied the possibility that the IR of $^{241}$Am capture reaction is lying around 0.85. This is consistent with the independent PIE results with PFR and PHENIX. Necessity of re-evaluation of the IR both in ENDF/B-VI and in JENDL-3.3 is suggested.

For the abundance ratio of $^{244}$Cm/$^{243}$Am, the present calculations were systematically underestimated by 10-20%. We have met the difficulty in measuring the ratio of Cm/Am, in which relatively large experimental error (about 10%) arose from alpha spectroscopy. We now try to improve the measurement accuracy by means of the isotope dilution analysis.

We carry on the analyses for the remaining samples, increase the number of results, and apply detailed calculation modeling. Those results are to be presented at the conference.

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## [267] Benchmarking of Uranium-238 Evaluations Against Spherical Transmission and (n,xn)-Reaction Experimental Data

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The neutron leakage spectra from Uranium-238 sphere of 24 cm outer and 8 cm inner diameters were measured at the Institute of Physics and Power Engineering with the central fusion and fission

type neutron sources. 14 MeV neutrons were produced by the pulsed D-T neutron generator KG-0.3, whereas fission neutrons by the $^{252}$Cf fast ionization fission chamber. The spectra of leaking neutrons were measured by the time of flight technique at flight path 4 m by a fast scintillation detector having the neutron threshold of 0.2 MeV.

Double differential neutron emission cross section from $^{238}$U(n,xn) reaction were measured at 14 MeV incident neutron energy employing the same experimental technique but a hollow cylinder uranium sample with diameter of 4.5 cm, wall thickness 0.3 cm and height 5 cm. The neutrons with energies above 0.5 MeV were detected at angles 30 to 150 degrees. Elastically scattered neutrons were subtracted from the energy spectra using the shape of the D-T source neutrons.

The experimental data were analysed by Monte-Carlo technique using the MCNP-4C code. A detailed three-dimensional model was elaborated to represent the neutron source, uranium sphere or sample and neutron detector. The corrections have been applied for the time-of-flight measurement technique, the response function of spectrometer in the case of neutron transmission experiment and for the multiple neutron scattering in the case of the U(n,xn) reaction measurement.

The neutron leakage spectra from U sphere with D-T and $^{252}$Cf neutron sources and U(n,xn) double differential cross sections at 14 MeV were compared with the transport calculations and the ENDF-B7 (preliminary version), JINER ('Maslov' evaluation), ENDF-B6, JEFF-3 and ENDL-85 libraries. It was found that the latest evaluations (ENDF-B7 and JINER) predict leakage spectra and emission cross section within 10-15% that is clearly less than earlier versions or libraries do.

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## [348] Comparison of Ramsauer and Optical Model Neutron Angular Distributions

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In a recent paper [1] it has been shown that the nuclear Ramsauer model does not do well in representing details of the angular distribution of neutron elastic scattering for incident energies of less than 60 MeV for $^{208}$Pb. We show that the default angular bin dispersion most widely used in Monte Carlo transport codes is such that the observed difference in angular shapes are on too fine a scale to affect transport calculations. The effect of increasing the number of Monte Carlo angle bins is studied to determine the dispersion necessary for calculations to be sensitive to the observed discrepancies in angular distributions. We also show that transport calculations are sensitive to differences in the elastic scattering cross section given by recent optical model fits of $^{208}$Pb data compared with older fits.

This work was performed under the auspices of the US. Dept. of Energy by Univ. of Cal., Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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## [37] Scaling Relations for the Hard Component of Light Hadron Scattering Spectra

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Much of the high energy portion of continuum spectra from (p,p'X), (p,nX), (pi,piX), (pi,pi0X) and (K+,K+X) reactions on complex nuclei can be understood as the result of quasifree scattering on single bound nucleons. The kinematic limits of this understanding and the role of attenuations and multiple scattering will be demonstrated by analyses of existing data, and the methods of analysis that yield simple scaling relations will be presented. These methods can serve as reliable models for at least part of the spectra for a wide range of hadron-nucleus cross sections.

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## [145] Status of the International Neutron Cross Section Standards File

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Progress achieved in the framework of the IAEA Co-ordinated Research Project (CRP) on improvement of the standard cross sections will be reported. The primary aim of this CRP is the international evaluation of the neutron cross section standards. An area of concern is the improvement of the evaluation methodology and to better understand the origin of a strong reduction of uncertainties observed in R-matrix model fits for light elements. New evaluations will be produced for the $^{6}$Li(n,t), $^{10}$B(n,$\alpha$), $^{10}$B(n,$\alpha_1$), $^{197}$Au(n,$\gamma$), $^{235}$U(n,f), $^{238}$U(n,f) standard reactions as well as the $^{238}$U(n,$\gamma$), and $^{239}$Pu(n,f) reactions that are simultaneously evaluated along with the standards due to the strongly coupled databases for these two reaction categories. Also independent R-matrix evaluations will be prepared for the H(n,n) and $^{3}$He(n,p) standard cross sections.

The methodology, codes, and experimental databases developed by W. Poenitz and G. Hale for the ENDF/B-VI standards evaluation project were taken as a starting point for this new evaluation activity. The new contributions of the current evaluation effort include: - use of theory to predict the position and widths of remote R-matrix poles to decrease an ambiguity in the R-matrix fit; - tests and inter-comparisons of various R-matrix and least-squares codes as well as their correction and updating; - studies of data uncertainty reduction and elimination of the non-physical effects leading to such reduction; - analyses of discrepant data and resolution of some of these discrepancies; - studies of the experimental database for the presence of the Peelle's Pertinent Puzzle (PPP) phenomenon and revision of both data and codes to minimize or eliminate biases that it may introduce; - updates to the experimental database by inclusion of new experimental data and corrections to some older measurements; - expansion of the energy range for the fission cross section database to 200 MeV along with a joint evaluation of both low- and high-energy standards; - adaptation of a least-squares procedure for combining the results of R-matrix fits for light-nuclei standards with least-squares fits for both light- and heavy-nuclei standards; - preparation of standards data files in convenient formats as is required by the major users.

A general trend observed for the new standards evaluation is a clear increase of most cross sections; the magnitude of the increase varies from less than a percent to a few percent.
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## [496] Measurement of the Absolute np Scattering Differential Cross Section with a Tagged Neutron Beam at Intermediate Energies

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The neutron-proton scattering database at intermediate energies is plagued by experimental inconsistencies and cross section normalization difficulties [1]. This situation has led to an undesirable state of affairs, wherein the most sophisticated partial wave analyses of the data [2] ignore the vast majority of measured cross sections, the literature is filled with heated debates concerning experimental and theoretical methods [3], theorists propose radical "doctoring" to "salvage" allegedly flawed experiments [4], and one of the most fundamental parameters of meson-exchange theories of the nuclear force — the charged pion-nucleon-nucleon coupling constant — hangs in the balance [1–3]. I will describe the techniques and results of a new measurement performed with a very different approach from earlier experiments to settle

the most worrisome discrepancies. The experiment involves a kinematically complete double-scattering measurement, carried out during the final year of operation of the Indiana University Cyclotron Facility's Cooler ring. Neutrons of about 190 MeV were produced by the $^2$H(p,n)2p reaction induced by a stored, electron-cooled proton beam in a deuterium gas jet target, permitting detection of the two low-energy recoil protons to tag and measure the four-momentum of each produced neutron. Energetic protons from np scattering induced in a secondary $CH_2$ target were detected (in coincidence with the tagging protons) in a forward detector array that spanned the entire c.m. angle range from 90 to 180°. A graphite target carefully matched in carbon density per unit area was frequently substituted for the $CH_2$ to permit an accurate background subtraction and reduce reliance on kinematic cuts to distinguish free from quasifree np scattering. These methods have allowed direct experimental determination of the absolute cross sections with a systematic uncertainty of order 2% and reliable measurement of the angular distribution shape for np backscattering. The results should settle the debate for np scattering and provide a good cross section standard for intermediate-energy neutron scattering.

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## [111] Forward-angle np scattering at 96 MeV and normalization of neutron-induced nuclear reactions

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The np scattering cross section - in particular at 180 degrees (c.m.), which corresponds to proton emission at 0 degrees in the lab - is used to normalize measurements of other neutron-induced cross sections, i.e., it is the primary standard cross section. In addition, it plays an important role in fundamental physics, because it can be used to derive a value of the absolute strength of the strong interaction in the nuclear sector, commonly expressed as the pion-nucleon (pNN) coupling constant. Previously, data from Uppsala covering 74–180 degrees have been published. Since part of the angular distribution was not covered, NN models were used to correct the normalization result for the undetected angular range, resulting in a 2 % uncertainty. If the entire angular range were known, it would have been possible to normalize the data to the total cross section directly by integration. This has motivated the present experiment on forward np scattering (0–84 degrees). Subtraction of data obtained with $CH_2$ and carbon targets has been used to obtain the np differential cross section. By measuring $CH_2$ and carbon in the same experiment, the elastic cross section ratio of hydrogen versus carbon can be obtained. Since the elastic cross section of carbon can be determined absolutely by a combination of differential, total and reaction cross section measurements, an independent cross-check of the absolute np cross section can be obtained.
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## [207] Particle leaking, cross-sections ratio $^{10}$B(n,$\alpha$)/$^{238}$U(n,fission), and excitation function of the reaction $^{10}$B(n,$\alpha$)$^7$Li at MeV energies

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The neutron-reaction standard $^{10}$B(n,$\alpha$)$^{7}$Li has been studied in the energy range between 1 MeV and 5 MeV at the 7 MV Van de Graaff accelerator of IRMM by using a gridded ionisation chamber (GIC) and signal digitisation. The aim was to obtain accurate data for the recently started IAEA Coordinated Research Project on the improvement of standard cross sections for light elements. The effect of particle leaking has been discovered and its implications investigated. Particle leaking arises from the simultaneous emission of reaction products in forwards angles and the inability of the detector to resolve multiple particles. It is an inherent property of all GIC spectrometers used for the study of (n, charged particle) reactions on light-element solid targets. The measurement of the cross section strongly benefits from it but the determination of other measurables is negatively affected. Forward angular distributions are truncated at large emission angles and look like depleted of reaction products in a region between a kinematically determined angle $\theta_0$ and 90°. The branching ratio $\alpha_0/\alpha_1$ can not be determined in the depleted region. The cross-sections ratio $^{10}$B(n,$\alpha$)/$^{238}$U(n,fission) has been measured and the excitation function of $^{10}$B(n,$\alpha$)$^{7}$Li determined by simultaneously detecting the charged particles from the boron disintegration emitted in the forward and the fission fragments emitted in the backward emission hemispheres respectively. Compared to the most recent versions of well known evaluations the IRMM cross sections show the best overall agreement with the data of JEF-2.2, are close to the values of JENDL-3.3, and strongly deviate from predictions of ENDF/B-VI.8 and JEFF-3.0.

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## [372] New Results for the $^{6}$Li and $^{10}$B Neutron Standard Cross Sections from R-matrix Analyses and Microscopic Calculations for the $^{7}$Li and $^{11}$B Systems

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As part of the IAEA-sponsored neutron standard cross section evaluation effort, we have undertaken new R-matrix analyses of reactions in the $^{7}$Li and $^{11}$B systems. The R-matrix parameters in these systems are compared with, and guided by, microscopic calculations that use semi-realistic nucleon-nucleon potentials in the Refined Resonating Group Model (RRGM).

The analyses include experimental data for all possible reactions open at excitation energies up to about 10.7 MeV in $^{7}$Li, and up to about 12.8 MeV in $^{11}$B. The effects of the three-body breakup channel, $n + d + \alpha$, appear to be important near the end of this range in the $^{7}$Li system, and they are taken approximately into account. The fits to the data included are reasonable, although some of the $t + \alpha$ scattering measurements, in particular, have uncertainties that probably are too small. Measurements of the $^{6}$Li$(n,t)^{4}$He angular distribution disagree substantially in the MeV neutron energy range where a number of overlapping resonances determine the shape of the integrated cross section. We will discuss the variances and covariances of these and other cross sections that result from the analyses.

In this mass range, computer-time limitations restrict the RRGM calculations to use semi-realistic $N - N$ forces, which can introduce artifacts associated with unphysical thresholds into the scattering calculations. However, by using non-orthogonal wave functions to determine the R-matrix poles and residues directly, these artifacts can be avoided. We compare first results of these calculations with the experimental parameters determined from the $^{7}$Li and $^{11}$B analyses.

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## [545] Recent Cross Section Evaluations in the Resonance Region at the Oak Ridge National Laboratory

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Resonance evaluations in the resolved and unresolved energy regions have been performed at the Oak Ridge National Laboratory using the computer code SAMMY. Several new features have been implemented in SAMMY. Among these features are the capability to accurately account for data resolution and the generation of resonance-covariance data in both the resolved and the unresolved energy regions. In the full paper an overview of the methodology used at ORNL in the resonance evaluations for U-233 (resolved resonance region), U-235 (unresolved resonance region), U-238 (resolved resonance region), and F-19 (resolved resonance region) evaluation, will be given.

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## [153] Systematic Analysis of Uranium Isotopes

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We describe recent LANL nuclear model calculations and evaluations of neutron reactions on uranium isotopes in the keV – 30 MeV range, for uranium isotopes from $^{232-241}$U. This work makes use of extensive sets of measurements for fission, $(n, xn)$ and capture, as well as fission probability data. The $^{235}$U$(n, f)$ standard cross section was revised on the basis of improved experimental data, and the fission cross sections of the uranium isotopes, as well as $^{237}$Np and $^{239}$Pu, were updated using the revised standard. Nuclear reaction model calculations were performed for the whole suite of uranium isotopes to allow us to take advantage of the systematical properties from isotope-to-isotope, which is especially useful for nuclides where few measurements exist. In addition to improving the neutron cross sections and energy-angle distributions, new prompt fission neutron spectra and prompt/delayed neutron multiplicity evaluations are included for several isotopes.

We shall focus on some of the critical evaluations, especially $^{233}$U, $^{235}$U, and $^{238}$U, where our evaluation work was performed iteratively with important feedback from integral data testing (critical assemblies in the fast and thermal region, and 14-MeV pulsed-spheres). Our new evaluations solve some long-standing problems, for example: (a) $^{238}$U inelastic scattering is better modeled, which has a positive impact on the criticality of thermal assemblies as well as faster assemblies; (b) $^{238}$U reflection is better modeled in the fast region; (c) criticality of fast systems involving $^{233,235,238}$U is accurately reproduced, including that of $^{233}$U. We will focus on the cross section improvements (including theory predictions) that have led to this improved performance.

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## [77] Multiplicities and spectra of prompt fission neutrons up to 200 MeV

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The energy distributions of prompt fission neutrons for $E_n$ up to 200 MeV are of great importance for the accelerator-driven system technologies of sustainable energy production and radioactive waste transmutation. Model calculations were performed to interpret the prompt fission neutron spectra (PFNS) of $^{232}$Th(n,f) and $^{238}$U(n,f) reaction for $E_n \lesssim$20 MeV recently [1]. Pre-fission $^{238}$U(n,xnf) reaction neutron spectra were calculated with a Hauser-Feshbach statistical model, $^{238}$U fission and (n,xn) reaction cross section data being fitted. The average energy of the pre-fission (n,nf) neutrons is shown to be rather dependent on $E_n$. For $E_n$= 6 - 9 MeV the lowering of PFNS average energy, which is due to the pre-fission (n,nf) neutrons, is reproduced. For $E_n$= 13 - 18 MeV a lowering of the measured PFNS average neutron energies was interpreted. Spectra of neutrons, evaporated from fission fragments, were approximated as a sum of two Watt' distributions. Recently energy distributions of prompt fission neutrons for incident neutron energies up to 200 MeV were reported [2], multiplicity data for $^{235}$U(n,f) and $^{238}$U(n,f) might appear soon [3]. We would extend our phenomenological approach up to 200 MeV. A self-consistent model on the basis of the energy balance with the incorporation of chance structure of fission would be employed [4]. It was verified below 20 MeV. The calculated values are compatible also with experimental data for $E_n \sim$ 20-50 MeV for the $^{232}$Th, $^{235}$U, $^{238}$U target nuclides. We will explore the energy dependence of the pre- and post-fission neutron multiplicities. Realistic calculations of average energies of pre-fission neutrons would be carried out for $E_n$ up to 200 MeV for the consistent neutron multiplicity analysis at high incident energies for (n,f) and (p,f) reactions. Importance of separate measurements for the $\nu_{pre}$ and $\nu_{post}$ for (n,f) and (p,f) reactions would be exemplified.

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## [221] Direct-Semidirect Neutron Capture Calculations Applied to R-Matrix Data Evaluations in the Resolved Resonance Region

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We present a method for computing direct-semidirect neutron radiative capture and its applications to R-Matrix evaluations of $^{19}$F, $^{27}$Al, $^{28}$Si, and $^{35,37}$Cl, performed by the Nuclear Science and Technology Data group at ORNL on neutron transmission and capture data measured at ORELA during the past few years. The method includes both direct and semidirect capture; the latter is a core-polarization term in which the giant dipole resonance is formed. We compare our method with that of T. Rauscher et. al, which has been commonly used in computations related to astrophysics, as well as in nuclear data evaluations.

For nuclear data evaluations in the resolved resonance region, where R-Matrix evaluations are commonly performed using the Sammy code, direct capture is significant in valleys between resonant capture peaks, as well as at very low neutron incident energy below the lowest resonance (e.g. thermal capture).

The experimental data for which the R-Matrix analyses are being performed is subject to background effects that at energies below 10 keV could be sufficiently large to obscure the direct capture cross section. Consequently, an accurate evaluation of TOF data requires a prediction of the direct capture cross section, to which end we apply our method.

This work was performed under the auspices of the U.S. Department of Energy by DE-AC05-00OR22725 and by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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## [95] Calculations of Neutron and Proton Induced Reaction up to 200 MeV for Target $^{238}$U

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In recent years, the accelerator-driven system (ADS) has been an interesting focus in nuclear physics, China has also paid great attention to this field. To satisfy the demands of intermediate energy nuclear data fromADS project of China, two programs for calculating nuclear data in medium energy region are being developed: MEND for medium-heavy nucleus ($Z < 71$) and MENDF for fission and subfission nucleus ($Z > 70$). Both programs are constructed within the framework of optical model, intranuclear cascade nucleon emission mechanism based on empirical formula, preequilibrium statistical theory based on exciton model and the evaporation model; the Hauser-Feshbach theory with width fluctuation correction is also introduced for first particle emission in low energy region, Bohr-Wheeler formula was used in fission width calculation. The direct inelastic and reaction cross section as well as angular distribution, which can be calculated with the code DWUCK4 and/or ECIS94, are as input for both MEND and MENDF.

In both programs, the projectile and emitting particle can be neutron, proton, $^{4}$He, deuteron, triton and $^{3}$He; all reactions in first, second, third, ... up to 18th particle emission and fission process are in considered. All reaction cross sections and energy spectra of 6 kinds of emitting particles, gamma rays and all kinds of recoil (residual) nuclei can be calculated, the double-differential cross section of 6 kinds of emitting particles can also be calculated with Kalbach systematics. Besides, in MENDF, the mass and charge distribution as well as the kinetic energy distribution of fission fragments, $\nu$-values and energy spectra of fission neutrons can also be calculated.

The calculations of neutron and proton induced reaction Up to 200 MeV for target $^{238}$U with MENDF are performed, the calculated results are generally in rather good accordance with experimental data and reasonable in physics.

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# Theory: Reaction Models

**Anasazi North**, Thursday 8:30–10:10

[498] Nuclear Models in FLUKA: Present Capabilities, Open Problems and Future Improvements
**A. Ferrari [Invited]**

[346] Preequilibrium Reactions with Complex Particle Channels
**C. Kalbach(Walker)**

[242] Pre-Equilibrium Cluster Emission with Pickup and Knockout
**E. Běták**

[166] Exciton Model Calculations up to 200 MeV: the Optical Model Shows the Way
**M.C. Duijvestijn**

# Measurements: Facilities

**Anasazi South**, Thursday 8:30–10:10

[531] LANSCE
**P. Lisowski [Invited]**

[535] Nuclear-data experimental programs at GSI
**K.-H. Schmidt [Invited]**

[440] The n_TOF Facility at CERN: Performances and First Physics Results
**V. Vlachoudis [Invited]**

# Applications: Fission Energy

**Sunset**, Thursday 8:30–10:10

[506] New Reactor Concepts and New Nuclear Data Needed to Develop Them
**S. Ganesan [Invited]**

[491] Recent Application of Nuclear Data to Fast Reactor Core Analysis and Design in Japan
**M. Ishikawa [Invited]**

[141] New Results on Helium and Tritium Gas Production From Ternary Fission
**O. Serot**

[216] A Noise Analysis Approach for Measuring Effective Delayed Neutron Parameters in the IPEN/MB-01 Reactor
**R. Diniz**

## [498] Nuclear models in FLUKA: present capabilities, open problems and future improvements

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The nuclear reaction models embedded in the FLUKA code can cover hadron, photon and neutrino induced nuclear interactions from energies as low as few tens of MeV up to several tens of TeV.

The application fields which are driving the development of these models are mostly the following:

- Basic research:
  - Neutrino physics
  - Exotic rare events (ie nucleon decays)
  - Cosmic ray physics
  - Simulation of complex experimental apparatus
  - Prediction and mitigation of background for experiments
- Accelerator Driven Systems
- Beam-machine interaction at accelerators
- Radioprotection at accelerators, both "prompt" radiation and induced radioactivity
- Dosimetry
  - Medium and high energy particle conversion coefficients
  - Commercial flight dosimetry
  - Hadron therapy
- Space radiation

FLUKA is currently in use in all these fields by several groups around the world. The present code is an attempt at satisfying the resulting requirements, which are complex and somewhat contradictory.

A (short) description of the main physics ingredients in the FLUKA nuclear models will be given, with emphasis on the intermediate energy range, covering in particular:

- The FLUKA Generalized IntraNuclear Cascade (GINC) and its differences with respect to traditional INC models
- Pion physics in FLUKA at inermediate energies
- The preequilibrium step
- The evaporation/fission/fragmentation step
- How the FLUKA nuclear models have been extended to "exotic" reactions (muon absorption, neutrino reactions, nucleon decays etc) and their importance for future experiments

Examples of performances will be presented for representative situations covering some of the most typical FLUKA applications, and emphasizing the relevance of the various physics steps.

Finally, the open problems and the main lines for the future development of FLUKA will be discussed.

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## [346] Preequilibrium Reactions with Complex Particle Channels

Constance Kalbach (Walker)

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Since the field of preequilibrium reaction studies was launched in 1966 by the seminal paper of J. J. Griffin, much progress has been made in understanding these reactions and in improving the predictive ability of model calculations. Yet most of the work considers only reactions with nucleons as both the incoming and outgoing particles. This paper describes efforts to improve the 1985 phenomenological description of reactions with deuterons, tritons, He-3 ions, or alpha particles in the entrance and/or exit channel. It utilizes new literature data and incorporates advances in the exciton model for reactions involving only nucleon channels. Interim results were incorporated in the code PRECO-2000.

Complex particle channels are difficult to treat because of the variety of reaction mechanisms that contribute. The mechanisms considered in PRECO are (1) emission during equilibration that is described by the exciton model, (2) direct transfer of one or more nucleons, (3) knockout and inelastic scattering involving cluster degrees of freedom, and (4) excitation of collective states (both spectroscopic and giant resonance). In addition, a preliminary formulation for complex particle breakup has been developed for incident deuterons. It will be included in the code after being extended to He-3 and alpha projectiles and after angular distributions have been considered.

This paper describes the current status of the models and presents comparisons with some of the many inclusive energy spectra studied. The data involve reactions at incident energies up to 63 MeV for neutrons, 90 MeV for protons, 80 MeV for deuterons, 41 MeV for He-3, and 140 MeV for alpha particles. The current models provide a significant improvement in predictive ability over earlier versions and will all be included in the next release of PRECO.

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## [242] Pre-equilibrium cluster emission with pickup and knockout

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We present a generalization of the Iwamoto-Harada-Bisplinghoff pre-equilibrium model of light cluster formation and emission in the course of nuclear reaction, which is enhanced by allowing for possible admixtures of knockout for strongly coupled ejectiles, like $\alpha$'s.

The model is able to attain the Weisskopf-Ewing formula for the compound nucleus decay at long-time limit; it keeps the philosophy of pre-equilibrium decay during the equilibration stage and describes the initial phase of a reaction as direct process(es) expressed using the language of the exciton model.

The idea is applied to several proton-induced reactions at energies between 20 and 100 MeV, to demonstrate its possibilities.

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## [166] Exciton model calculations up to 200 MeV: the optical model shows the way

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We present a pre-equilibrium model for nucleons with incident energies from 7 to 200 MeV, for nuclides in the mass range $24 \leq A \leq 209$. This is accomplished by means of a global parameterization for the two-component exciton model [1] which, together with the complementary compound and direct reaction mechanisms, enables to describe continuum energy spectra over the whole emission energy range. A new energy-dependent form for the average squared matrix element $M^2$ is proposed, which is physically justified by the optical model. The imaginary part of the optical potential forms a direct measure for the probability to be absorbed into non-elastic channels. As such it may be related to the nucleon-nucleon interaction in matter and, hence, to the collision probability of a particle inside the nucleus. This collision probability is exactly the quantity one aims to describe phenomenologically with the aid of an average squared matrix element in exciton calculations. Recently, a new global optical model has come on the market [2]. This optical model is valid up to 200 MeV and, consequently, can be used to guide the development of a new matrix element parameterization, which removes problems encountered with older parameterizations that apply in more restricted energy ranges. The model, furthermore, contains surface effects which depend on the type of projectile and the target mass. This is inspired by the work by Kalbach [3], but deviates in the parameterizations used. Another feature that enables the large energy range of our analysis is the generalization of multiple pre-equilibrium processes up to any order of particle emission. To constrain our parameterization as much as possible and to assess the performance of our model, we have compared it with an extensive experimental data collection of (n,xn), (n,xp), (p,xn) and (p,xp) spectra.

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## [531] LANSCE

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The Los Alamos Neutron Science Center, or LANSCE, is a National User Facility. Experiments at LANSCE use beam from the 800-MeV proton linear accelerator to execute an extraordinarily broad program of basic and applied science. Recent investments in the LANSCE complex have provided essential infrastructure upgrades and new scientific capabilities in each of three major areas: Proton radiography (pRad), which uses the proton beam directly from the accelerator to image dynamic materials properties, the Lujan Neutron Scattering Center (Lujan Center), which produces a moderated neutron source (meV to keV) for neutron-scattering research to investigate properties of materials, biological molecules, and condensed matter physics and to support a program of nuclear astrophysics and fundamental physics; and the Weapons Neutron Research Facility (WNR), which produces an unmoderated neutron source (keV to 800 MeV) for research in nuclear science and technology, as well as for testing industrial components such as computer chips in a high-energy neutron field. During 2004, LANSCE commissioned a facility for producing medical radioisotopes as well as an ultra-cold neuron source. This gives LANSCE the ability to produce and use neutrons with energies that range over 14 orders of magnitude. This talk will describe the facility and give highlights of recent research related to nuclear science and technology.

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## [535] Nuclear-data experimental programs at GSI

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At GSI, Darmstadt, an extended series of measurements on nuclear-reaction products has been performed. The work is based on an innovative experimental approach, which exploits the unique technical installations of GSI: The accelerator complex provides heavy-ion beams with relativistic energies, which impinges on a reaction target, and a high-resolution magnetic spectrometer is used to identify the reaction products in-flight and to determine their kinematic properties. In addition, the storage ring provides a powerful tool for determining their ground-state masses.

The most important features of this experimental approach are

- full indentification in $A$ and $Z$ of the primary reaction products before their radioactive decay,
- complete coverage of the velocity distribution of each individual nuclide with no lower energy threshold, which allows reconstructing complete invariant-cross-section distributions,
- simultaneous identification of both fission fragments in $Z$,
- precision measurements of nuclear masses.

The major experimental results are:

- Systematic overview on the nuclide production in fragmentation-evaporation and fragmentation-fission reactions of several systems, ranging from $^{56}$Fe + $^{1}$H to $^{238}$U + Pb.
- Nuclide production in fission of $^{238}$U from excitation of the GDR.
- Systematic study of the evolution of fission channels as a function of $Z$ and $A$ of the fissioning system.
- Direct insight into transient effects in fission.
- Fingerprints of multifragmentation in invariant-cross-section distributions.
- Exploring the isospin degree of freedom in relavistic heavy-ion reactions.
- Precision velocity measurements in quasielastic and quasiinelastic peripheral collisions.
- Manifestation of nuclear structure in the condensation process of heated nuclear matter while cooling down in the evaporation process into the super-fluid phase.
- Information on the equation of state of nuclear matter from the response of the spectators to the participants blast.
- Systematic determination of nuclear masses on extended regions of the chart of the nuclides.

These results are relevant for nuclear technology. In addition, they provide an improved basic understanding of nuclear reactions and the properties of cold and heated nuclear matter.

The FAIR project will provide essentially enhanced experimental conditions for this kind of research.

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## [440] The n_TOF facility at CERN: Performances and first physics results

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The neutron Time of Flight (nTOF) facility at CERN is a source of a wide range (1 eV$< E_n <$250 MeV) flux of neutrons, generated by spallation of 20 GeV/$c$ protons onto a solid lead target. The goal of the nTOF is to provide unprecedented precision in neutron kinetic energy determination, which will in turn bring the much-needed precision in neutron-induced cross-section measurements.

The unique features of the nTOF facility (instantaneously very intense neutron flux, low duty cycle, high resolution and low background) makes possible the measurement of highly radioactive isotopes usually available in small quantities. Such measurements are vital for a range of studies in fields as diverse as nuclear technology, astrophysics and fundamental nuclear physics.

In this paper, the characteristics of the nTOF facility will be described, together with the main features of the high performance detectors and acquisition system used for cross-section measurements, and a summary of the results and experience acquired during the first years of operation.

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## [506] New reactor concepts and new nuclear data needed to develop them

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Developments of new reactor designs for utilization of thorium, such as the Advanced Heavy Water Reactor, especially demand creation of new nuclear data for all the isotopes of thorium fuel cycle. Improved nuclear data are essential to support new initiatives such as the international project on innovative nuclear reactors and fuel cycles (INPRO) that aims to support the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century. The detailed pursuit of development of Generation IV nuclear energy systems that offer advantages in the areas of economics, safety, reliability and sustainability require significantly improved nuclear data. The development of Accelerator Driven Sub-critical Systems proposed by Carlo Rubbia and others require significant amount of new nuclear data in extended energy regions and improvement of the presently available nuclear data. The quality assurance in design and safety studies in nuclear energy in the next few decades and centuries require new and improved nuclear data with high accuracy and energy resolution. The paper presents, from the perspective of the author, an overview of some of the improvements in nuclear data required for a sound scientific basis of advanced nuclear systems. Also, from the perspective of benchmarking and integral validation of nuclear data, presented briefly is the status of thorium irradiations performed in PHWRs in India and new results of post-irradiation analyses available thus far.

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## [491] Recent Application of Nuclear Data to Fast Reactor Core Analysis and Design in Japan

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Recently, some improvements of the nuclear data application to the fast reactor core field have been accomplished in Japan.

Development of group constants and analytical tools

First, an ABBN-type 70-group constant set has been used conventionally for fast reactor analysis in Japan. In order to improve the applicability of the group constant to various types of reactor cores and to treat exactly the interference effect of resonance peaks between mixed isotopes in a cell, a new cell calculation system with an ultra-fine group constant set which has more than 100,000 group structure

has been developed and opened to public. Second, to process the ENDF-type covariance file including resonance parameters, angular scattering distribution, a code ERRORJ, which is an extended version of the NJOY-ERRORR module, has been developed and released through OECD/NEA. Third, an analytical system to calculate the cross-section sensitivity coefficients of various core parameters including burnup characteristics and Doppler reactivity has been prepared as one part of neutronics system for fast reactor analysis. The sensitivity coefficient is a very powerful tool to understand some physical mechanism caused by nuclear data and to analyze the effect of difference between libraries.

Consistent evaluation of nuclear data by fast reactor experimental database

Recently, a set of fast reactor experimental database, most of which can be opened to public, has been compiled and completed by JNC. The database includes, the JUPITER large-size fast core critical experiment program using ZPPR facility at ANL-Idaho, the MOZART middle-size core project at ZEBRA facility in UK, the FCA small-core critical experiments at JAERI in Japan, the BFS critical experiments at IPPE in Russia, the MASURCA critical experiments at Cadarache, in France, the physics test and operational data of the JOYO experimental power reactor in Japan, the old Los Alamos small core experiment, etc. JNC is also evaluating the burnup composition changes of the JOYO driver fuels and minor actinide samples. The JENDL library was systematically applied to these various integral data and the performance and consistency of the C/E(calculation/experiment) values were investigated in detail.

Improvement of prediction accuracy and application to fast reactor design study

To utilize the above critical experimental data and power reactor operational experience to the design work, the most powerful method is to adjust the cross-sections based on the Bayesian theory and least-square technique, where all related information including C/E values, experimental and analytical errors, sensitivity coefficients of various experimental cores and parameters, and cross-section covariance, is synthesized with physical consistency. Here the adjusted cross-section set is called a "unified cross-section" set which means a physical combination of the integral experimental information with differential nuclear data. A newest unified cross-section set, ADJ2000R, has been successfully developed and used in the design calculation of the FBR cycle feasibility study in Japan. Since a lot of experience has got from the nuclear data application to the design study in Japan, JNC will express some opinions and future needs to the nuclear data study from a user viewpoint in the presentation.

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## [141] New Results on Helium and Tritium Gas Production From Ternary Fission

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In the fission process, the two heavy fragments are accompanied by a Light Charged Particle (LCP) roughly two to four times every thousand events. These particles constitute an important source of helium and tritium production in nuclear reactors. Data concerning this production are requested by nuclear safety specialists and also by physicists in order to improve our understanding of the LCP emission process and to infer information related to the fission process itself.

In the present paper, we report results obtained from various campaigns of measurements performed in order to enlarge the database related to the $^{4}$He and $^{3}$H emission probabilities. These measurements concern both thermal neutron induced fission reactions as well as spontaneous fission decays. For spontaneous fission, data are reported for nuclides ranging from $^{238}$Pu up to $^{252}$Cf. For neutron induced fission, results cover target nuclei between $^{229}$Th and $^{251}$Cf.

Based on these and other results, new semi-empirical relations are proposed. They show that the triton emission probability (t/B) as well as the alpha emission probability (LRA/B) after correction for alpha-clustering correlate fairly well with two parameters: the fissility parameter ($Z^2/A$) and the average total fission neutron multiplicity ($\langle\nu\rangle$). Nevertheless, these correlations are only valid if spontaneous fission data and neutron induced fission data are considered separately, suggesting that the excitation energy of the fissioning nucleus must be taken into account. In this way, t/B and LRA/B could be predicted for fissioning systems not investigated so far. Results obtained from this work will be included in the Fission Yields data file of the European library JEFF3.

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## [216] A Noise Analysis Approach for Measuring Effective Delayed Neutron Parameters in the IPEN/MB-01 Reactor

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The purpose of this work is to introduce a new in-pile experiment for the determination of the relative abundances (Betas) and decay constants (Lambdas) of delayed neutrons through the noise analysis technique. The experimental procedure consists of obtaining the Cross Power Spectral Density (CPSD) and the Auto Power Spectral Density (APSD) from the signals of two compensated ionization chambers in the frequency range from 0.005 to 50.0 Hz approximately. Assuming the point kinetic model in the detectors position we can write the theoretical expression for the CPSD and the APSD's and the experimental data can be fitted by means of a least-square procedure. The fitting parameters are the Beta(i) or Lambda(i), i=1..6, for a six group model.

With these experimental spectral densities the least-squares procedure was able to fit 5 out of 6 of the relative abundances. The relative abundance of the first group must be fixed in order to achieve convergence of the fitting. For the decay constants occurs the same i.e., the first decay constant (the group of longest half-life) must be fixed. The fixed parameters are those of the three nuclear data libraries, namely ENDF/B-IV, ENDF/B-VI.8 (LANL revised) and JENDL 3.3. To make possible the comparison between theory and experiment the library decay constants must be fixed for the fitting of Betas and vice-versa.

The parameters were obtained with great accuracy (small errors due to the fitting procedure) but the comparison with calculated results from the above libraries presents some deviation, being the higher one on the order of 20% for the lowest half-life. However, even the comparison between libraries also presents higher discrepancies. The experimental technique also allows the determination of the effective beta without the need of the Diven factor and the power normalization.

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# Theory: Reaction Models

**Anasazi North**, Thursday 10:30–12:10

[201] TALYS: Comprehensive Nuclear Reaction Modeling
**A. Koning [Invited]**

[298] Recent Progress of the Liege Intranuclear Cascade Model
**J. Cugnon [Invited]**

[421] Recent Development of the Nuclear Reaction Model Code Empire
**M. Herman**

[331] Comprehensive Calculations of Heavy Ion Interactions
**F. Cerutti**

[430] Improved Intranuclear Cascade Models for the Codes CEM2k and LAQGSM
**S.G. Mashnik**

# In Memory of S. Raman

**Anasazi South**, Thursday 10:30–12:10

[534] The Research Career of Subramanian Raman at ORNL
**Bertrand [Invited]**

[502] Structural Evolution in Nuclei: The Importance of a Systematic Perspective
**R.F. Casten [Invited]**

[527] Applications of High Resolution Gamma Ray Spectroscopy
**H.G. Börner [Invited]**

[492] Successful Collaborations with Dr. S. Raman in Research on Nuclear Data in Japan
**M. Mizumoto [Invited]**

# Applications: Fission Energy

**Sunset**, Thursday 10:30–12:10

[513] Neutron Data Measurements for Energy Applications and Nuclear Waste Transmutation at JRC-IRMM
**A. Plompen [Invited]**

[ 66] ORNL Evaluation of the Resonance Parameters of $^{238}$U in the Neutron Energy Range from 0 keV to 20 keV and Its Impact in Reactor Calculations
**H. Derrien [Invited]**

[377] Nuclear Data for Short Lived Actinides: The $^{233}$Pa ($T_{1/2}$=27 days) Case
**M. Aiche**

[328] Integral Experiments Analysis for Validation and Improvement of Minor Actinide Data for Transmutation Needs
**G. Palmiotti**

[365] Measurement of Neutron Transmission Through Iron Spheres
**T.N. Massey**

## [201] TALYS: Comprehensive nuclear reaction modeling

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The advent of fast computers has enabled the numerical implementation of even the most sophisticated nuclear models. TALYS is a nuclear reaction program created at NRG Petten, the Netherlands and CEA Bruyères-le-Châtel, France, which simulates nuclear reactions that involve neutrons, gamma-rays, protons, deuterons, tritons, helions and $\alpha$-particles, in the 1 keV – 200 MeV energy range. A suite of nuclear reaction models has been implemented into a single code system, enabling us to evaluate basically all nuclear reactions beyond the unresolved resonance range. An overview is given of the main nuclear models used, which includes among others our newly developed optical models, various compound nucleus models, fission and the pre-equilibrium model, all driven by a comprehensive database of nuclear structure parameters. The predictive power of the code is demonstrated by comparing the calculated results with a very diverse set of experimental observables. The production of nuclear data libraries, using a sinlge standard ENDF-6 formatting procedure, is briefly mentioned. Our aim is to show that TALYS represents a robust computational approach to cover the whole path from fundamental nuclear reaction models to the creation of complete data libraries for nuclear applications. We will also present our views on future theory developments needed to more accurately model various phenomena.

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## [298] Recent Progress of the Liege Intranuclear Cascade Model

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The Liege Intranuclear cascade model has recently evolved to a numerical code INCL4, which, without any parameter tuning, is able to give good results for an impressive set of data concerning spallation reactions in the 100 MeV to 2 GeV range of incident energies[1]. These data include total reaction cross-sections, neutron and proton double differential cross-sections, particle multiplicities, residue mass and charge spectra, isotopic distributions and residue recoil energy distributions, for proton-induced as well as deuteron-induced reactions. The success of this version of the Liege INC code comes mainly from the introduction of a diffuse surface, from an improved treatment of the Pauli principle and from a self-consistent determination of the stopping time, i.e. the time at which the cascade is stopped and the evaporation code is started. This feature seems to free the model from the introduction of a so-called pre-equilibrium module.

Here, we report on new advances in the development of the Liege INC model. They cover:
(1) An investigation of the behaviour of the model at low energy. It will be shown that the model gives reasonable results for neutron and proton double differential cross-sections down to 40-50 MeV of incident energy, i.e. much lower that the theoretical limit of validity, provided the handling of the Pauli principle is further improved, especially by a refined evaluation of the phase space occupancy.
(2) The introduction of a nuclear mean field that depends upon the isospin and the energy of the nucleons, as suggested by the optical model phenomenology[2]. It will be shown that these modifications decrease the multiplicity of the neutrons emitted in the cascade stage and increases the excitation energy left in the remnant at the end of this stage. This helps to improve the predictions of the model for the residue mass spectrum in the fragmentation domain.
(3) An improvement of the pion production. A potential for the pions is introduced, as well as an improvement of their re-interaction accounting for medium corrections. Results will be shown and discussed.
(4) Predictions of correlations. Two types of correlations are investigated in view of the forthcoming PISA and SPALADIN experiments at Julich and GSI, respectively. They relate to angular correlations of fast particles and to correlations of the multiplicity of fast protons and neutrons (and of the energy carried by these particles) with the mass of the residue. This type of observables is expected to constrain INC+evaporation models quite stongly, as they are sensitive to the way energy is released in the two stages of the reaction process. Results will be discussed.

[1] A. Boudard, J. Cugnon, S. Leray and C. Volant, Phys. Rev. C66 (2002)044605.
[2] E. Gadioli and P. Hodgson, Pre-equilibrium Nuclear Reactions, Clarendon, Oxford, 1992.

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## [421] Recent Development of the Nuclear Reaction Model Code Empire

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EMPIRE-II is a system of codes intended as a general theoretical tool to be used in basic research and nuclear data evaluation for calculation of nuclear reactions in the broad range of incident energies and projectiles. It was design to contain state of art nuclear reaction modeling, being at the same time very easy to use. A full ENDF-6 formatted file and its graphical comparison with available experimental data can be obtained with just a few mouse clicks and key strokes.

Empire-II includes most of major nuclear reaction mechanisms, such as spherical optical model (SCAT2) and Coupled Channels (ECIS), Multi-step Direct (ORION + TRISTAN), NVWY Multi-step Compound, exciton model (DEGAS), Monte Carlo preequilibrium emission, and the full featured Hauser-Feshbach model with width fluctuation correction (HRTW). A comprehensive library of input parameters, based on RIPL-2, covers nuclear masses, optical model parameters, ground state deformations, discrete levels and decay schemes, level densities, fission barriers (BARFIT), moments of inertia (MOMFIT), and gamma-ray strength functions. The results can be converted into the ENDF-6 format using the accompanying code EMPEND. Relevant EXFOR entries are automatically retrieved during the calculations. By default, plots comparing experimental results with the calculated ones are produced using the extended PLOTC4 code linked to the rest of the system through a series of preprocessing codes and bash-shell scripts. Interactive plotting is possible through the powerful ZVView package. Easy operation of the whole system is assured by the graphic user interface written in Tcl/Tk.

In the present contribution recent developments, extending functionality and applicability of the system will be discussed. These include: (i) new algorithm for disentangling emission spectra into exclusive components, (ii) treatment of the recoils spectra, (iii) state of the art handling of the fission channel, (iv) merging resonance region into the final evaluation, (v) extended formatting and plotting capabilities, and (vi) new user graphic interface.

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## [331] COMPREHENSIVE CALCULATIONS OF HEAVY ION INTERACTIONS

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Accurate knowledge of reactions which may occur when two heavy ions interact is of crucial importance in many trans-disciplinary fields, particularly in medicine and space physics. In these cases one needs to know not just the results of particular processes, as investigated in many experiments, but what happens in a natural process to which all possible reaction mechanisms contribute. The collection of this information requires a considerable experimental and theoretical effort. In fact, a theoretical calculation to be really usable should be able to reproduce large sets of data in wide energy and mass ranges. While such calculations are extensively made for nucleon induced reactions, heavy ion interactions are much less studied.

In this contribution an account is given of some results which we have recently obtained in a series of investigations aimed to contribute to fill this gap in our knowledge, considering heavy ion interactions from the Coulomb barrier up to relativistic energies and adopting different approaches.

Reactions induced by light projectiles at few tens of MeV/n are studied by very simplified mean field calculations coupled with the Boltzmann Master Equation theory, describing the preequilibrium

deexcitation of the composite system created by the interaction of two nuclei. Its MonteCarlo implementation allows to predict a wide variety of cross sections, i.e. both double differential spectra of light particles and intermediate mass fragments and quite demanding observables, like excitation functions for the production of individual heavy residues.

Reactions between medium and heavy nuclei at several hundreds of MeV/n are analysed interfacing the FLUKA code with a Relativistic Quantum Molecular Dynamics model.

These calculations seem to suggest that it may be within our reach to provide a comprehensive description of large sets of data and predict with fair accuracy cross sections of unmeasured reactions.

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## [430] Improved Intranuclear Cascade Models for the Codes CEM2k and LAQGSM

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During the last years, we have developed at LANL an improved version of the Cascade-Exciton Model (CEM) of nuclear reactions realized in the code CEM2k and the Los Alamos version of the Quark-Gluon String Model (LAQGSM) to describe reactions induced both by particles and nuclei at energies up to hundreds of GeV/nucleon for a number of applications. We have tested and benchmarked the CEM2k and LAQGSM codes against a large variety of experimental data on particle-particle, particle-nucleus, and nucleus-nucleus reactions and have compared their results with predictions by other currently available models and codes. Our comparisons show that the CEM2k and LAQGSM codes have predictive powers comparable to other currently used codes and describe many reactions better than other codes; therefore both our codes can be used as reliable event-generators in transport codes for applications. The CEM2k code was incorporated two years ago into MCNPX, while both CEM2k and LAQGSM are currently being incorporated into the transport codes MARS and LAHET, and we plan to incorporate both our codes into MCNP5 and LAQGSM into MCNPX in the near future.

This does not mean that our codes are perfect and without problems. Here, we present some improvements to the intranuclear cascade models of CEM2k and LAQGSM we performed recently with a primary aim to better describe the physics of nuclear reactions striving meanwhile to get also a better agreement with available experimental data. First, we have incorporated the photonuclear mode from CEM2k into LAQGSM to extend its applicability to photonuclear reactions not previously modeled in LAQGSM. Next, we developed new approximations to describe more accurately experimental elementary energy and angular distributions of secondary particles from hadron-hadron and photon-hadron interactions using available data and approximations published by other authors. Then, we studied and refined the treatments of the Pauli principle, refraction and reflection from the nuclear potential, details of the nuclear density and the momentum distribution of intranuclear nucleons. Finally, to consider reactions involving very highly excited nuclei ($E^* > 3$ MeV/A), we have incorporated into CEM2k and LAQGSM the Statistical Multifragmentation Model (SMM), as a possible reaction mechanism occurring after the preequilibrium stage. Illustrative results will be presented, unsolved problems will be discussed, and further necessary work will be outlined.

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## [534] The Research Career of Subramanian Raman at ORNL

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Subramanian "Ram" Raman, a distinguished nuclear physicist and senior staff member of the Physics Division at Oak Ridge National Laboratory (ORNL), died April 8, 2003. In June 1966, Raman joined the staff at ORNL working in the Nuclear Data Project. This position provided him insights into important open questions in nuclear structure physics, and the power of "horizontal" compilations of properties across a broad range of nuclei. These insights would guide Raman's research interests throughout his 36-year career at ORNL.

As shown by his great variety of publications, Raman's research career was marked by an intense interest in all areas of nuclear physics. He published papers on topics ranging from detailed nuclear

structure to giant resonances to the search for superheavy nuclei to the scattering of heavy ions. His research resulted in over 200 published papers and over 3000 citations of his work. It is however, his nuclear data evaluations, both horizontal and vertical, that we most often remember. His most often cited papers deal with the evaluation and systematics of nuclear data and he helped establish many of the "rules" and guidelines for assignment of nuclear level properties. An overview of Raman's work at ORNL will be presented.

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## [502] Structural Evolution in Nuclei: The Importance of a Systematic Perspective

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One of the signature features of Raman's work was the love and exploitation of nuclear systematics as a tool to discern interesting structural phenomena and to understand better the evolution of structure with nucleon number. Such a tool, properly used, can be extremely powerful, especially when data are correlated with a physically meaningful variable that yields simple and compact trajectories. It can reveal trends that reflect basic elements of nucleonic interactions, it can reveal nuclei with special symmetries, or anomalous nuclei, and it can point to possibly incorrect measurements. This talk will focus on several uses of correlations of nuclear data, illustrating the above ideas. Particular aspects to be discussed are proton-neutron interactions, quadrupole collectivity, the search for phase transitional behavior and critical point nuclei, and a new mapping of collective nuclear structure across large parts of the nuclear chart, leading to a discovery of an "arc of regularity" characterizing certain nuclei lying adjacent to others that exhibit chaotic spectra.

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## [527] APPLICATIONS OF HIGH RESOLUTION GAMMA RAY SPECTROSCOPY

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At the Institut Laue Langevin gamma rays emitted after neutron capture can be recorded with ppm resolution. This is achieved by diffracting gamma rays on highly perfect Si and/or Ge crystals. The high resolving power allows one to observe the tiny Doppler effects caused in de-excitation processes of nuclei following neutron capture. Thereby recoils can be induced by the subsequent emission of gamma rays or, in various beta decay scenarios, by the emission of electrons and/or neutrinos. The structure of the measured Doppler profiles depends on the magnitude of the original recoil velocity, the slowing down time of the recoiling nuclei in the sample and the lifetimes of the excited nuclear states that are populated subsequently to the recoil. Ultra high resolution gamma ray measurements have given rise to applications in nuclear, fundamental and condensed matter physics. We will present some of the currently possible applications.
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## [492] Successful Collaborations with Dr. S. Raman in Research on Nuclear Data in Japan

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Since early 1970, Dr. Raman visited Japan many times and has established good and fruitful relations with many scientists from universities and institutions of Japan in the nuclear data and nuclear physics fields. Those of the institutions that he visited are Institute of Nuclear Study (The University of Tokyo), Osaka University, Tokyo Institute of Technology (TIT), Japan Atomic Energy Research Institute (JAERI), Japan Nuclear Cycle Development Institute (JNC) and others. Many Japanese young researchers also stayed in Oak Ridge National Laboratory (ORNL) and worked together with him. We all

remember him as a very active and warmhearted person. For many years, we had been enjoying to work with Dr. Raman and had opportunity to count on his extensive knowledge and experience in the nuclear data and other many research fields; nuclear spectroscopy, neutron capture cross section measurement, prompt neutron capture $\gamma$ ray activation analysis and study of thermophysical properties of transuranium alloys.

In particular, JAERI and ORNL have conducted comprehensive studies for nuclear data measurements and evaluation of actinides and the development of minor actinide contained fuel. For these measurements, JAERI needed high-purity actinide isotope samples, such as Pu, Np, Am and Cm for reactor physics and sample irradiation experiments. Dr. Raman helped us to negotiate with DOE to borrow these valuable samples. Irradiation experiments were carried out under the US-UK fast reactor program. Dr. Raman also initiated the irradiation program and played major role in the project. After the formal agreement between JAERI and ORNL in 1988 to jointly carry out actinide studies, it took twelve years to complete the chemical analysis and numerical evaluation of analyzed data. During this period, Dr. Raman visited JAERI every year to discuss the results obtained at that time. These discussions were really a powerful locomotive to complete the project. The paper on this study was finally submitted to Nuclear Science & Engineering and accepted immediately without any corrections requested. The published results are now used as the variable data base to improve the reliability of minor actinide cross sections.

At the Conference, the successful collaborations in research and personal reminiscences that we had with Dr. Raman will be presented.

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## [513] Neutron data measurements for Energy Applications and Nuclear Waste Transmutation at JRC-IRMM.

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Studies in nuclear energy and transmutation of radioactive waste require neutron data for conceptual and performance studies, to determine the viability of advanced ideas such as an Accelerator Driven System and to fix the safety margins of any new concepts. IRMM's neutron data measurement program addresses data needs associated with Accelerator Driven Systems, management of radioactive waste, the thorium fuel cycle, high temperature reactors and safety issues of conventional reactors1. Ongoing and recently completed activities include capture and total cross section measurements for $^{127,129}$I, $^{206}$Pb, $^{232}$Th, precision total cross section measurements for $^{240,242}$Pu, inelastic scattering measurements for $^{52}$Cr, $^{58}$Ni, $^{209}$Bi and $^{207}$Pb, (n,2n) measurements for $^{207}$Pb, and (n,xp), (n,x$\alpha$) and (n,xn) cross section measurements with the activation technique. Capture, total and inelastic cross section measurements make use of the pulsed white neutron source Gelina, whereas activation cross sections are determined at the Van de Graaff laboratory. An overview will be given of the above mentioned activities and an outlook will be provided for the measurement foreseen for the near future. The latter include determinations of the $^{209}$Bi(n,$\gamma$)$^{210m,g}$Bi and $^{241}$Am(n,$\gamma$)$^{242m,g}$Am and additional (n,2n$\gamma$) and (n,n'$\gamma$) reaction cross sections determinations at Gelina or the VdG by use of HPGe detectors with acquisition systems based on fast digitizers

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## [66] ORNL EVALUATION OF THE RESONANCE PARAMETERS OF $^{238}$U IN THE NEUTRON ENERGY RANGE FROM 0 keV TO 20 keV AND ITS IMPACT IN REACTOR CALCULATIONS.

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The $^{238}$U neutron resonance parameters currently used in the most recent evaluated neutron data libraries are those obtained by Moxon and Sowerby in the framework of a task force formed in 1982 by the Nuclear Energy Agency Nuclear data committee (NEANDC) with the aim of eliminating the discrepancies in the neutron widths and in the experimental capture cross sections. In 1994 the NEANDC concluded that the major discrepancies were removed by the work of the task force, and the Moxon-Sowerby evaluation was accepted. Recently it was found that most of the libraries (ENDF/B-VI-8, JEFF3-0 and JENDL3-2) show a systematic and still unexplained keff underprediction for thermal LWR. Accordingly, it was decided, in the framework of a Working Party on International Data Evaluation Cooperation (WPEC), to reexamine the $^{238}$U resonance parameters along with some other nuclear data (mainly $^{235}$U, $H_2O$, $^{16}$O). As a participation of ORNL in this international effort, and also in the framework of the ORNL Criticality Safety Program, a new evaluation of the $^{238}$U resonance parameters was performed in view of the improvement of the data in the energy range thermal to 10 keV (Moxon-Sowerby energy range) and to extend the resolved resonance range to 20 keV. The analysis of the experimental data was performed with a new version of the Bayesian code SAMMY allowing an accurate calculation of the multiple scattering effects in the experimental capture cross section and of the Doppler broadening of the resonance by using a crystal lattice model. The preliminary results, obtained from the sequential SAMMY analysis of the Olsen et al. and of the Harvey et al. ORELA high resolution transmission data, and of de Saussure et al. capture cross section data, in the energy range thermal to 20 keV, were combined to some new evaluations of the cross sections in the high energy range (Bruyeres-Le-Chatel, France , Los Alamos National Laboratory, USA). The calculation using the new files showed a remarkable improvement in reactivity predictions compared to the previous evaluations.

The objective of the paper is:

1/ to give a short description of the new evaluation of the resonance parameters and to compare the calculated cross sections to those calculated with the previous evaluations. The resonance parameters reproduce a thermal capture cross section value of 2.68 b compared to the value of 2.71 b in ENDF/B-VI, JEFF-3 and JENDL-3, and the infinitely diluted resonance capture integral is lower by about 1%. The elastic scattering cross section is higher by about 2% on average in the energy range up to 20 keV.

2/ to give the results of various benchmarks calculations performed with the new resonance parameters associated to the most recent evaluations of the cross sections in the unresolved and high energy regions.

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## [377] Nuclear Data for Short Lived Actinides: The $^{233}$Pa ($T_{1/2}$=27 days) case.

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The thorium-$^{233}$U fuel cycle is subject to a renewal of interest. It is indeed strongly believed that nuclear reactors using this fuel might provide safer and cleaner nuclear energy compared to the present uranium fuelled reactors. The primary reaction of importance in the thorium cycle is the one producing the fissile nucleus $^{233}$U from neutron capture on $^{232}$Th. The net production of $^{233}$U is controlled by the 27 days half-life of $^{233}$Pa: the fertile nucleus $^{232}$Th is transformed into the fissile nucleus $^{233}$U after neutron capture and two successive beta decays. Thus, the $^{233}$U inventory will depend on the neutronic properties

of $^{233}$Pa because every neutron captured by $^{233}$Pa will affect neutron economy and will cause $^{233}$U to be lost. When we initiated these studies, the $^{233}$Pa(n,f) and $^{233}$Pa(n,$\gamma$) cross sections were poorly known and the nuclear data libraries, built on theoretical predictions, exhibited large discrepancies. The lack of reliable experimental data could be explained by the high specific activity of $^{233}$Pa and the build-up of its daughter product $^{233}$U. To overcome these problems we have used the transfer reaction technique to measure the fission probability of $^{234}$Pa formed in the reaction $^{232}$Th($^{3}$He,p)$^{234}$Pa. The neutron induced fission cross section for the $^{233}$Pa+n reaction has been deduced from the product of this experimentally determined fission probability with the compound nucleus cross section determined from dedicated optical model calculations. Several years ago, this method has been used successfully by Cramer and Britt1) in order to estimate the neutron induced fission of short lived targets. The experiments have been performed with the IPN Orsay tandem accelerator. The ($^{3}$He,p) exit channel has been identified with the $\Delta$E-E technique, the fission fragments in coincidence with the protons have been detected with an efficient solar cell based multidetector. The experimental data will be presented and compared (when available) with existing direct neutron measurements. Preliminary indirect cross section for the $^{233}$Pa(n,$\gamma$) will be presented too. Future extension of the transfer reaction technique to highly radioactive actinides (such as $^{242,244}$Cm isotopes) will be discussed.

1. J.D. Cramer and H. C. Britt . Nucl. Sci. Eng. 41 (1970) 177.

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## [328] Integral Experiments Analysis for Validation and Improvement of Minor Actinide Data for Transmutation Needs

Giuseppe Palmiotti[1], Massimo Salvatores[1], Jean Tommasi[2]

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The fuel form to be used in advanced nuclear systems dedicated to transmutation will contain a high fraction of Pu and Minor Actinides (MA). High quality cross sections are crucial for these isotopes, to provide reliable neutronic design and fuel cycle assessment. Basic data are available for these isotopes but a detailed validation is needed to quantify their reliability. In the framework of the CEA/DOE international collaboration on the Advanced Fuel Cycle Initiative, a very comprehensive effort is underway to exploit the unique CEA experimental data base in order to validate and improve the current set of cross sections (JEF and ENDF libraries), branching ratios and decay constants. The cleanest and most useful irradiation experiments available in the CEA data base are the PROFIL and TRAPU programs, which cover the full range of Pu and Am isotopes and some Cm data. Previous papers have reported on the experiment analysis. The observed C/E's on the final densities of the measured isotopes for the different basic data files have indicated some large discrepancies that a subsequent sensitivity/uncertainty analysis has attributed to specific cross sections of actinides. Among them: $^{238}$U (n,2n), capture cross sections of higher plutonium isotopes , $^{241}$Am, $^{243}$Am, and $^{242}$Cm. capture cross sections. More recently, in order to provide trends and indications that cross section evaluators can exploit, a simulated adjustment, at one group level, has been carried out using the TRAPU experimental results. The one group cross sections before and after adjustment for JEF2.2 and ENDF/B-VI have shown consistency with values that tend to converge. In the full paper results relative to a more comprehensive analysis of irradiation experiments (TRAPU, PROFIL), critical masses (including new data from the Neptunium Sphere Experiment), and spectral indices measurements will be provided along detailed energy adjustment suggestions. The impact on design and fuel cycle parameters will be underlined.

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## [365] Measurement of Neutron Transmission Through Iron Spheres

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We have measured the transmission of neutrons through two iron spheres with several different sources. We have used a quasi-monoenergetic source with 3.0, 5.0, and 7.0 MeV deuterons incident on a deuteron gas cell and 5.1 MeV protons incident on a $^{15}$N gas cell. These reactions were found to be the most suitable sources below 11 MeV for minimizing the energy spread of the neutrons produced.

The Ohio University Beam Swinger Facility was used in these measurements. This allowed a single fixed detector to be used for all angles in a well shielded time-of-flight tunnel. This also allowed a large reduction in the background from room scattered neutrons. NE213 and lithium glass detectors, that were calibrated relative to the neutron spectrum from the B(d,n) or Al(d,n) reaction were used in the experiments. The B(d,n) and Al(d,n) spectra have been measured relative to the primary neutron cross section standard, $^{235}$U(n,f).

We have measured the source reactions at a number of angles to allow modeling that is being done for these measurements. The transmitted neutrons have been measured for the two different spheres at several angles for the source reactions used. The results of this investigation will be presented.

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# Processing, Testing, and Validation of Evaluated Data

**Anasazi North**, Thursday 13:30–15:10

[536] Testing New Actinide Cross Sections Proposed for ENDF/B-VII
**R.E. MacFarlane [Invited]**

[213] Nuclear Data for Improved LEU-LWR Reactivity Prediction
**A. Courcelle [Invited]**

[266] Benchmark Test for JENDL-3.3 Library by Analyses of A Series of Experiments at The Fast Critical Assembly (FCA) of JAERI
**S. Okajima**

# Applications: Safety

**Anasazi South**, Thursday 13:30–15:10

[537] TBC
**Briggs [Invited]**

[515] Nuclear Data Activities in Support of the DOE Nuclear Criticality Safety Program
**R.M. Westfall [Invited]**

[317] New Neutron Cross-Section Measurements at ORELA for Improved Nuclear Criticality Calculations
**K.H. Guber [Invited]**

# Theory: Off Stability

**Sunset**, Thursday 13:30–15:10

[416] *Ab Initio* Large-Basis No-Core Shell Model
**B.R. Barrett [Invited]**

[332] Nuclear Level Densities far from Stability
**S.M. Grimes [Invited]**

[507] Global Microscopic Models for Nuclear Reaction Calculations
**S. Goriely [Invited]**

## [536] Testing New Actinide Cross Sections Proposed for ENDF/B-VII

Robert MacFarlane

*Los Alamos National Laboratory*

Our Nuclear Theory Group has worked over the last several years to improve the ENDF/B actinide cross sections, especially as measured against the famous series of fast-spectrum critical experiments performed at Los Alamos under such names as Godiva, Jezebel, the Flattops, and Bigten. The new evaluations (see Paper No.153 in this conference for details) include changes in the high-energy fission cross sections, nubar, elastic scattering, inelastic scattering, fission spectra, and delayed neutrons that combine to significantly improve the calculated results for the Los Alamos critical assemblies. As a happy byproduct of this work, we found that the new evaluations also removed about half of a long-standing descrepancy in calculations of thermal-reactor critical experiments using lattices of low-enriched uranium oxide rods. In the meantime, work at the Oak Ridge National Laboratory (see Paper No.66) has resulted in new proposed resonance parameters for U-238. When these low-energy data are combined with the new high-energy data from Los Alamos, they have the effect of removing most of the rest of the problem for thermal lattices. Although more work will be done at both Los Alamos and Oak Ridge, including making the evaluations consistent with the new standards, the results presented in this talk provide promise that ENDF/B-VII will result in good improvements for users at both high and low neutron energies.

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## [213] Nuclear data for improved LEU-LWR reactivity prediction

Arnaud Courcelle

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Subgroup 22 of the Working Party on International Nuclear Data Evaluation Co-operation (WPEC) has been set up to investigate the reasons for the systematic reactivity underprediction of thermal LEU-LWR (Low Enriched Uranium, Light Water Reactor). This $k_{eff}$ underprediction ($\approx 0.5\%$) is observed with the most recent nuclear data libraries (ENDFB/VI.8, JENDL3.3 and JEFF3.0). A special mailing list called **ueval** has been created to collect contributions on this subject. (see the website at www.nea.fr/lists/ueval).

The aim of this paper is to summarize the work done. Activities were restricted to the improvement of reactivity prediction of system using fresh uranium fuel (i.e the problem of $k_{eff}$ prediction during depletion was not investigated). This collective work was based on several assumptions :

- The observed $k_{eff}$ is not likely the consequence of numerical approximations in reactor calculation methods. This point was checked using Monte-Carlo approach and accurate pointwise representation of nuclear data.
- Given the number of experiments investigated (mostly from the ICSBEP handbook) and the different kinds of experimental methods used to achieve critical state, the present reactivity bias is not believed to come from experimental errors in criticality measurements.

The Working Group focused on nuclear data evaluations of main isotopes impacting thermal benchmarks calculations : U235, U238, H2O and O16. The following specific points have been studied :

- Following the work of the WPEC/Subgroup 4, new preliminary improved evaluations of U238 inelastic data have been distributed and tested against integral benchmarks.
- The thermal capture cross-section of U238 has been revisited, new resonance parameters of U238 have been proposed for testing purpose. Tests have ensured that the modifications of U238 capture cross-section in the thermal and resolved range were still compatible with U238 integral measurements (U238 capture rate ratios measured in critical facilities and Pu239 build-up prediction in depleted PWR assembly).

After a continuing effort to test successive versions of those preliminary nuclear data files, it has been demonstrated that a significant improvement of LEU-LWR reactivity prediction is achieved without worsening the prediction of other systems (such as intermediate spectra, highly enriched uranium

systems). Work is still needed to test the performance of these new data at a larger scale using a broader range of benchmarks (especially in the fast neutron spectrum).

The provisional conclusions of this collective work are expected to contribute towards the improvement of the future versions of nuclear data Libraries. Recommendations concerning the needs for integral and experimental measurements are provided and topics for future investigation are also suggested.

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## [266] Benchmark Test for JENDL-3.3 Library by Analyses of A Series of Experiments at The Fast Critical Assembly (FCA) of JAERI

Shigeaki Okajima, Masahiro Fukushima, Masaki Andoh

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The evaluated nuclear data library JENDL-3.3 was released in May 2002. Some of the main revised data from JENDL-3.2 library are as follows: (1) the elastic scattering cross section of graphite, (2) the resonance parameters of structural materials and (3) the resonance parameters, the fission cross section and the capture cross sections of U-235. To validate those data, benchmark tests on keff values and the central fission rate ratios were made by analyzing a series of experiments at the Fast Critical Assembly (FCA) of JAERI.

Eleven different FCA cores with simple composition and geometry have been selected from a viewpoint of benchmark test; eight uranium fueled cores, FCA Assembly IX-1 to IX-7 and XIX-1, and three plutonium fueled cores, FCA Assembly, X-1, X-2 and XIX-3.

In the test a continuous-energy Monte Carlo code MVP was used to minimize the uncertainties of core geometrical modeling and of data processing for the multi group cross sections generation. Each core is modeled as precisely as possible in the calculations. The number of neutron histories was 2 million in all of keff calculations and 5 million in the central fission rate ratios calculations.

The calculated results were compared between JENDL-3.3 and JENDL-3.2 libraries. In the core composed with 93% enriched uranium and diluent material of graphite, the ratio between calculation and experiment (C/E) for keff decreases as the neutron spectrum becomes soft. On the other hand this tendency is not found in the JENDL-3.2 calculations. This spectrum dependency might be caused by the revised capture cross section of U-235. Further investigation is required to make the sensitivity study in detail. In the other uranium cores, there is no large discrepancy in the C/E values between JENDL-3.3 and JENDL-3.2. In the plutonium cores the JENDL-3.3 gives better C/E values than the JENDL-3.2.

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## [537] TBC

Briggs

*TBC*

To be confirmed.

Email:

## [515] NUCLEAR DATA ACTIVITIES IN SUPPORT OF THE DOE NUCLEAR CRITICALITY SAFETY PROGRAM

R. M. Westfall[1], R. D. McKnight[2]

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The DOE Nuclear Criticality Safety Program (NCSP) provides the technical infrastructure maintenance for those technologies applied in the evaluation and performance of safe fissionable material operations in the DOE complex. These technologies include an Analytical Methods element for neutron transport as well as the development of sensitivity/uncertainty methods, the performance of Critical Experiments, evaluation and qualification of experiments as Benchmarks, and a comprehensive Nuclear Data program coordinated by the NCSP Nuclear Data Advisory Group (NDAG).

The NDAG gathers and evaluates differential and integral nuclear data, identifies deficiencies, and recommends priorities on meeting DOE criticality safety needs to the NCSP Criticality Safety Support Group (CSSG).Then the NDAG identifies the required resources and unique capabilities for meeting these needs, not only for performing measurements but also for data evaluation with nuclear model codes as well as for data processing for criticality safety applications.The NDAG coordinates effort with the leadership of the National Nuclear Data Center, the Cross Section Evaluation Working Group (CSEWG), and the Working Party on International Evaluation Cooperation (WPEC) of the OECD/NEA Nuclear Science Committee. The overall objective is to expedite the issuance of new data and methods to the DOE criticality safety user. This presentation describes these activities in detail, with examples based upon special studies being performed in support of criticality safety for a variety of DOE operations.

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## [317] New Neutron Cross-Section Measurements at ORELA for Improved Nuclear Criticality Calculations

Klaus H. Guber, Luiz C. Leal, Royce O. Sayer, Paul E. Koehler, Timothy E. Valentine, Herve Derrien, Jack A. Harvey

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Concerns about using existing cross-section evaluations from libraries such as ENDF/B-VI or JENDL-3.2 for nuclear criticality calculations have been a prime motivator for new cross-section measurements at the Oak Ridge Electron Linear Accelerator (ORELA). Most of the older neutron cross section data show deficiencies or do not cover the energy range that currently is important for a wide variety of applications.

Many of the evaluations found in these libraries were derived from measurements made with poor time-of-flight resolution, and also the description of some data in the neutron energy range above several tens of keV is crude. This impacts not only the resolved resonance region but also the unresolved region, and could lead to problems in processing data from the libraries and also to erroneous Maxwellian average cross sections. As a consequence, these evaluated data may not have sufficient quality for nuclear criticality calculations wherein effects such as self shielding, multiple scattering, or Doppler broadening can be important. Furthermore, many evaluations for nuclides having small neutron-capture cross sections are erroneously large because the neutron sensitivity of the old measurements was underestimated. Although their neutron capture cross sections are small, these nuclides can be important absorbers in many criticality calculations, so accurate determinations of these cross sections can be very important.

Over the last three decades ORELA has produced many neutron induced cross section data. It is the only high power white neutron source with excellent time resolution still operating in the USA, and is ideally suited for experiments to measure neutron total and capture cross sections in the energy range from 1 eV to $\sim$600 keV.

In this paper the facility and experimental setup at ORELA will be described and the results of the new measurements for Fluorine and Potassium will be discussed

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## [416] *AB INITIO* LARGE-BASIS NO-CORE SHELL MODEL

Bruce R. Barrett[1], Petr Navrátil[2], Andreas Nogga[3], W. E. Ormand[2], Ionel Stetcu[1], James P. Vary[4]

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The large-basis no-core shell-model (NCSM) approach allows one to perform *ab initio* calculations of the properties of nuclei up to mass $A = 16$. This technique is based on a separation between the model space and the excluded space at either the two-body or three-body cluster level[1,2]. Results converged to very high accuracy have been obtained with this procedure for the $A = 3$ and $A = 4$ systems. For the $A = 3$ system we have also performed calculations including a two-pion-exchange three-nucleon (NNN) interaction. Recently calculations have been performed at the three-body cluster level for $p$-shell nuclei, with and without a NNN interaction. In the former case, we can investigate the influence of NNN forces on nuclear properties as well as study how various models for the NNN interaction differ in their description of nuclear structure. In the latter case, we are able to look at how convergence properties of our NCSM calculations are improved by increasing the cluster level. Application of our *ab initio* NCSM approach to $p$-shell nuclei has allowed us to study, for example, the soft-dipole mode in $^6$He and the properties of exotic nuclei, as well as to obtain a good approximation to the low-lying properties for the nuclei investigated[3]. Work is in progress to expand the model spaces and obtain even greater convergence as well as on exact calculations of other effective operators. Because we are able to exactly determine the structure of the effective interactions and operators employed in our investigations of these lighter nuclei, we hope to gain insight into how to extrapolate this knowledge to construct similar interactions and operators for heavier nuclei.

1. P. Navrátil, J. P. Vary and B. R. Barrett, Phys. Rev. Lett. **84**, 5728 (2000); Phys. Rev. C **62**, 054311 (2000).
2. B. R. Barrett, P. Navrátil, W. E. Ormand and J. P. Vary, in the Proceedings of the XXVII Marzurian Lakes School of Physics, Krzyże, Poland, September 2-9, 2001, Acta Phys. Pol. **B33**, 297 (2002), and references in therein.
3. P. Navrátil and W. E. Ormand, Phys. Rev. Lett. **88**, 152502 (2002); Phys. Rev. C **68**, 034305 (2003).

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## [332] Nuclear Level Densities far from Stability

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We have recently completed studies of all nuclei with known levels with 20<A<100. The level densities were as a function of A and Z-$Z_0$ where Z is the nuclear charge and $Z_0$ is the equilibrium charge for a given mass. These studies indicated that the level density will be lower off the line of stability based on the known levels at low excitation energy. This formulation of the level densities has been incorporated in the Hauser-Feshbach program, HF2002. Work is now in progress for a series of experiments to investigate the dependence of nuclear level densities off of the line of stability at higher excitation energies. Current plans call for measurements using the ($^3$He,n) reaction, ($^{12}$C,p) and ($^{12}$C,alpha). Future investigations are planned using radioactive beams and a carbon target. This work was supported under U.S. D.O.E. grant No. DE-FG02-88ER40387.

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## [507] Global microscopic models for nuclear reaction calculations

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Important effort has been devoted in the last decades to measure reaction cross sections. Despite such effort, many nuclear applications still require the use of theoretical predictions to estimate experimentally unknown cross sections. Most of the nuclear ingredients in the calculations of reaction cross sections need to be extrapolated in an energy or/and mass domain out of reach of laboratory simulations. In addition, some applications often involve a large number of unstable nuclei, so that only global approaches can be used. For these reasons, when the nuclear ingredients to the reaction models cannot be determined from experimental data, it is highly recommended to consider preferentially microscopic or semi-microscopic global predictions based on sound and reliable nuclear models which, in turn, can compete with more phenomenological highly-parametrized models in the reproduction of experimental data.

The latest developments made in deriving such microscopic models for practical applications are reviewed. It mainly concerns nuclear structure properties (masses, deformations, radii, etc...), nuclear level densities, $\gamma$-ray strength functions as well as fission barriers and level densities at the fission saddle points. For each of these quantities, the microscopic predictions are compared with more phenomenological approaches, as those recommended by the IAEA database known as the Reference Input Parameter Library (RIPL). The impact of such microscopic nuclear inputs on capture cross sections is also discussed.

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# Evaluation Techniques

**Anasazi North**, Thursday 15:30–17:30

[ 9] Proton Interactions with Nuclei to Probe the Neutron Matter Distribution of the Nucleus
**K. Amos**

[429] A New Method For Estimating Neutron Reaction Cross Sections Based on Wick's Limit
**F.S. Dietrich**

[120] Upgrades to the R-Matrix Code SAMMY
**N.M. Larson**

# Application: Non-Proliferation

**Anasazi South**, Thursday 15:30–17:30

[102] Signatures of Fissile Materials: High-Energy Gamma Rays Following Fission
**S.G. Prussin [Invited]**

[522] Verifying the Comprehensive Nuclear-Test-Ban Treaty by radioxenon monitoring
**A. Ringbom [Invited]**

[511] Photon and Neutron Based Active Interrogation of Highly Enriched Uranium
**C.E. Moss [Invited]**

[479] Development of Innovative Nuclear Reactor Technology to Produce Protected Plutonium with High Proliferation Resistance and Verification of Nuclear Data
**T. Yoshida**

# Nuclear Theory: Advances in Calculational Methods

**Sunset**, Thursday 15:30–17:30

[519] Statistical Properties of Nuclei by the Shell Model Monte Carlo Method
**Y. Alhassid [Invited]**

[538] Microscopic Approaches to Light Nucleus Reactions
**J.A. Carlson [Invited]**

[517] Frontiers of Shell-Model Description for Atomic Nuclei
**M. Honma [Invited]**

## [9] Proton interactions with nuclei to probe the neutron matter distribution of the nucleus.

Ken Amos, Steven Karataglidis

*University of Melbourne, Australia*

Analyses of intermediate energy nucleon-nucleus scattering made using coordinate space nonlocal optical potentials obtained by full folding medium modified effective $NN$ interactions are sensitive to the target nucleon densities used in that folding. As the effective interaction and the structure details are all preset and no a posteriori adjustment or simplifying approximation is made to the folded optical potentials, the observables obtained are predictions. The procedure, under inverse kinematics, is able to explain observed data from radioactive beam experiments in which exotic, halo nuclei, are scattered from Hydrogen targets. However, when one has proton, neutron, and electron scattering form factors to assess putative ground state structures, those model structures of the target are particularly well tested. Results probing the ground state structure of $^{208}$Pb in particular, reveal that the comparisons to measured data suggest most strongly that the neutron r.m.s. radius is 5.62 fm, and the neutron skin thickness is 0.17 fm. Predictions of integral observables as well as of angular distributions made using those optical potentials compare very well with observed data for energies in the range above noticeable excitation of giant resonances to 300 MeV. The latest results for stable as well as some exotic neutron/proton rich nuclei will be shown.

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## [429] A New Method For Estimating Neutron Reaction Cross Sections Based on Wick's Limit

Frank S. Dietrich[1], John D. Anderson[1], Rudolf W. Bauer[1], Steven M. Grimes[2]

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The neutron reaction cross section $\sigma_{reac}$, also known as the nonelastic cross section, is important for applications but very difficult to measure accurately. In particular, obtaining $\sigma_{reac}$ by subtracting the elastic from total cross sections is subject to large systematic and statistical errors. We present a new method for obtaining $\sigma_{reac}$ based on such a subtraction, but in which the errors in the two terms are correlated by the use of Wick's limit, which relates the total and elastic cross sections. The reaction cross section may be written as a function of three independent quantities: $\sigma_{tot}$, the total cross section; $F$, the measured ratio of zero-degree differential elastic to angle-integrated elastic cross section; and $\eta$, the fractional deviation of the true zero-degree differential cross section from its Wick's-limit approximation. The resulting expression is

$$\sigma_{reac} = \sigma_{tot} - (1+\eta)F(k/4\pi)^2\sigma_{tot}^2, \tag{1}$$

where $k$ is the wave number of the projectile. The correlation between the two terms reduces the contribution to the error in $\sigma_{reac}$ from $\sigma_{tot}$ to a very small value. In practical cases the dominant error contribution is from $F$, and may be in the 1 to 2 % range. We have studied the range of validity of this method, which introduces a weak model dependence through the use of Wick's limit, by using a simple analytic (Ramsauer) model, as well as optical models. As an example, we have estimated the neutron reaction cross section on $^{208}$Pb at 7, 20, 22, and 24 MeV as $2.393 \pm 0.045$, $2.477 \pm 0.046$, $2.538 \pm 0.044$, and $2.450 \pm 0.044$, respectively. These results used the elastic angular distributions reported by R. W. Finlay *et al.*, Phys. Rev. C**30**, 796 (1984). The resulting uncertainties are below 2%. Further examples of this technique will be shown.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, and Ohio University under contract No. DE-FG02-88ER40387.

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## [120] Upgrades to the R-Matrix Code SAMMY

Nancy M. Larson

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The analysis code SAMMY is widely used for parameterization and understanding of neutron- and charged-particle-induced cross section data in the resolved and unresolved resonance regions. This paper

will report on advances made in the development of this code. An overview of the main features of SAMMY will be presented, with emphasis on options recently added to the code. These features can be divided into four categories: (1) theoretical cross sections, (2) experimental effects, (3) fitting procedure, and (4) input/output and other pre- or post-processing functions.

(1) In the resolved-resonance region (RRR), calculation of theoretical cross sections is generally performed using R-Matrix theory in the Reich-Moore approximation. In the unresolved-resonance region (URR), SAMMY uses Hauser-Feshbach theory with width fluctuations, using Froehner's FITACS code as basis.

R-Matrix theory is inherently limited to nuclear reactions involving a compound nucleus. When there is a direct component to the capture cross section, SAMMY now permits this to be added as a user-supplied numerical function of energy.

(2) In the RRR, experimental conditions cause the measured quantity to be quite different from the theoretical cross sections, and these conditions must be simulated in the analysis code. SAMMY includes a wide variety of options for this purpose; among the recent additions is an option to use crystal-lattice Doppler broadening for situations where the free-gas model is not adequate.

(3) Improvements to the fitting procedure used in SAMMY and other analysis codes, in particular with regard to the proper treatment of data covariance information, will be reported. Enhancements in SAMMY options for use of implicit data covariance matrices will be briefly described here, and the entire topic explored more fully in separate paper.

(4) As more options are created for SAMMY, the input has become more complicated. A streamlined version of input (including the particle-pair information separately from the channel quantum numbers) is now available. An auxiliary code SAMQUA, coauthored by colleagues from the French Atomic Energy Commission at Cadarache, can be used for assistance in preparing input for SAMMY.

Two new formats, approved by the Cross Section Evaluation Working Group during the 2003 meeting, now make it possible to translate any SAMMY evaluation into the Evaluated Nuclear Data Files. The "Compact Covariance Matrix" format can be used for storing resonance-parameter covariance information in an approximate fashion for those cases where the size of the matrix prohibits storage of the complete matrix. The "R-Matrix Limited" format can be used to report R-Matrix resonance parameter values in the case where there are several entrance channels, more than two exit channels, one or more threshold reactions, and/or charged-particle channels. The code SAMRML can be used to read resonances parameters from this format and calculate cross sections and sensitivity matrices (partial derivatives).

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## [102] Signatures of Fissile Materials: High-Energy Gamma Rays Following Fission

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The spectral and temporal dependence of beta-delayed gamma rays in the range E > 3.0 MeV from thermal-neutron induced fission are shown to be characteristic signatures of $^{235}$U and $^{239}$Pu. For interrogation of large sea-going cargo containers filled with hydrogenous materials, beta-delayed gamma rays can offer an increase in sensitivity for detection of these materials and other fissile materials by as much as 1000 – 10000 compared to the detection of beta-delayed neutrons.

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## [522] Verifying the Comprehensive Nuclear-Test-Ban Treaty by radioxenon monitoring

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The chemical inertness of noble gases allows them to escape from an underground nuclear explosion more easily than isotopes produced in solid form. Most fission gases decay within seconds, but a few

($^{133}$Xe, $^{135}$Xe, $^{133m}$Xe and $^{131m}$Xe) have half-lives long enough to allow detection at large distances. Radioxenon analysis has therefore been included in the verification regime for the Comprehensive Nuclear Test-Ban Treaty (CTBT). This verification system will provide worldwide monitoring for evidence of nuclear explosions and includes 321 monitoring stations of which 40 will be used for radioxenon monitoring. An overview of the verification system will be presented and the political and scientific challenges in this context will be briefly discussed. The establishment of the verification system for CTBT has prompted the development of a new generation of fully automatic radioxenon sampling and analysis systems in a few countries, and several systems have been installed in the verification system in the framework of the International Noble Gas Experiment (INGE). One of the systems participating is the Swedish Automatic Unit for Noble gas Acquisition (SAUNA). Principles and scientific challenges in using sampling and analysis of radioxenon as a verification tool are discussed using SAUNA as an example.

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## [511] Photon and Neutron Based Active Interrogation of Highly Enriched Uranium

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The physics of photon and neutron based active interrogation of highly enriched uranium (HEU) using the delayed neutron re-interrogation method will be described. Two sets of active interrogation experiments were performed using a set of sub-critical configurations of concentric HEU metal hemi-shells. One set of measurements used a linear accelerator based bremsstrahlung photon source as an active interrogation source. The second set of measurements used a pulsed 14-MeV neutron generator as the active source. The neutron responses were measured for both sets of experiments. The operational details and results for both measurement sets will be described. Simulations can be tested by comparison with these measurement sets and then used to design detection systems for HEU.

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## [479] Development of Innovative Nuclear Reactor Technology to Produce Protected Plutonium with High Proliferation Resistance — Requirement and Validation of Nuclear Data

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Future Nuclear Energy will not be able to go forward without settlement of such issues as disposal of spent fuel (including interim storage issues), confinement or transmutation of radioactive wastes and nuclear proliferation. In order to resolve these problems, solutions of spent fuels and wastes and development of protected nuclear systems with enhanced non-proliferation capability are needed. For this purpose, a new concept called PPP (Protected Plutonium Pqroduction) has been proposed. This concept consists of fuel ($^{239}$Pu) production from $^{238}$U neutron capture and $^{238}$Pu production for fuel protection from $^{237}$Np neutron capture.

$$\underset{\text{(Fuel Production)}}{\text{n} + {}^{238}\text{U}} \Rightarrow {}^{239}\text{Pu}/{}^{238}\text{Pu} \Leftarrow \underset{\text{(Fuel Protection).}}{{}^{237}\text{Np} + \text{n}}$$

The aim of this study is to develop advanced nuclear reactor technology by dispersing $^{237}$Np, presently treated as HLW, into U fuel for reduction of HLW, for achievement of high burn-up and for production of inherently protected plutonium.

For confirmation of the PPP Principle, irradiation tests of $^{237}$Np-U mixed samples are planned in the advanced test reactor (ATR) of INEEL. ATR is suitable for the short term irradiation test because of its high thermal flux level of $1 \times 10^{15}$ n/cm$^2$-sec. Post irradiation examinations (PIE) are also planned in ANL-W to obtain the nuclide composition data of Np, Pu, U, Am, Cm, which are needed to verify nuclear data and reactor core design method.

In this program, as for nuclear data, cross-sections, delayed neutron data and FP/ Alpha decay heat will be investigated from both the microscopic and macroscopic viewpoints. As integral tests, PIE data will be used in the analysis of irradiation experiments and the sample worth of $^{237}$Np will be measured by using Tank-type Critical Assembly (TCA) and Fast Critical Assemblies (FCA) of JAERI.

Present uncertainty of thermal capture cross-section of $^{237}$Np reaches up to 10%. This uncertainty should be reduced to several percent for reactor core design. The followings will be performed to ensure the calculation accuracy of the core with $^{237}$Np.

1. Improvement of reliability of the $^{237}$Np, $^{238}$Pu neutron cross-section data
2. Improvement of the energy release data for $^{237}$Np, $^{238}$Pu including the FP decay heat
3. Evaluation of the delayed neutron data for $^{237}$Np and $^{238}$Pu

The effect of nuclear data uncertainty of $^{237}$Np on core physics characteristics will be studied by using currently available nuclear data files, e.g. JENDL-3.3, ENDF/B-VI and JEF-2.2 and the results will be presented in the forthcoming conference.

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## [519] Statistical properties of nuclei by the shell model Monte Carlo method

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We use quantum Monte Carlo methods in the framework of the interacting nuclear shell model to calculate the statistical properties of nuclei at finite temperature and/or excitation energies. With this approach we can carry out realistic calculations in much larger configuration spaces than are possible by conventional methods.

A major application of the methods has been the microscopic calculation of nuclear partition functions and level densities, taking into account both correlation and shell effects. Our results for nuclei in the mass region $A \sim 50$–70 are in remarkably good agreement with experimental level densities without any adjustable parameters and are an improvement over empirical formulas. We have recently extended the shell model theory of level statistics to higher temperatures, including continuum effects. We have also constructed simple statistical models to explain the dependence of the microscopically calculated level densities on good quantum numbers such as parity. Thermal signatures of pairing correlations are identified through odd-even effects in the heat capacity and in the moment of inertia.

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## [538] Microscopic Approaches to Light Nucleus Reactions

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Quantum Monte Carlo methods, when combined with realistic models of nuclear interactions, provide an excellent description of light nuclear spectra up to mass $A$=12. We are presently extending these methods to treat low-energy scattering, including evaluations of resonance energy levels and widths. Results in the mass 5 system will be shown, future prospects outlined. The goal of developing these methods is to reliably predict reaction rates that are very difficult to measure experimentally.

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## [517] Frontiers of shell-model description for atomic nuclei

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The nuclear shell model has been one of the most powerful tools for the study of nuclear structure. Once a suitable effective interaction is given, the shell model can describe various nuclear properties accurately and systematically in a unified framework, covering many nuclei in the model space of interest. It is useful not only for the analysis of experimental data, but also to predict unobserved properties of unstable nuclei.

In conventional shell model calculations, we use a complete set of many-body bases and diagonalize the Hamiltonian matrix. The applicability of such a method has been limited to relatively light nuclei or those near the closed shell, because of the explosive increase of the basis dimension. Owing to recent developments in computational facilities and numerical calculation techniques, most of the $pf$-shell nuclei are now in the scope of exact $0\hbar\omega$ calculations. The current frontier of such direct calculations is in the middle of the $pf$-shell ($A \sim 60$), where the maximum $M$-scheme dimension reaches to two billion.

On the other hand, various approximation methods have been developed to overcome the dimensionality problem. We have proposed the Monte Carlo shell model (MCSM)[1], which enables us to carry out the shell model calculations with reasonable accuracy in much larger model spaces and with more valence nucleons. The MCSM has been successfully applied to various problems such as the shell evolution in the exotic nuclei around $N = 20$, the spherical-deformed shape coexistence around $^{56}$Ni, the unified description of $pf$-shell nuclei, and microscopic studies of the quadrupole collective motion in heavy nuclei.

The success of the shell model depends crucially on the choice of the effective interaction. The microscopic theory for deriving it from the nucleon-nucleon potential is insufficient especially for cases of many valence nucleons. Therefore it is needed to include the information form many-body data empirically for deriving a reliable effective interaction. In that sense, the experimental data and the shell model description can be developed complementarily, leading to our deeper understanding of various nuclear properties.

[1] T. Otsuka, M. Honma, T. Mizusaki, N. Shimizu and Y. Utsuno, Prog. Part. Nucl. Phys. **47** 319-400 (2001).
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# Theory and Evaluation

**Anasazi North**, Friday 8:30–10:10

[205] Microscopic Scattering Calculations and Data Analysis in Light Nuclei
**H.M. Hofmann**

[222] Level Density Corrections for Missing and Spurious Levels
**U. Agvaanluvsan**

[543] Neutron Capture Cross Sections: From theory to experiments and back
**A. Mengoni**

[551] TBC
**O.T. Grudzevich**

# Measurements and Experimental Techniques

**Anasazi South**, Friday 8:30–10:10

[ 91] Recent Results on the Measurements of the P-odd Correlations in the Capture of Slow Polarized Neutrons by $^{6}$Li and $^{10}$B
**Y.M. Gledenov**

[254] Distribution of Prompt Neutron Emission Probability for Fission Fragments in Spontaneous Fission of $^{252}$Cf and $^{248,244}$Cm
**A. Vorobyev**

[388] Neutron Capture Cross Sections for the Re/Os Clock
**M. Mosconi**

[ 49] GENIUS Test Facility for Dark Matter Search Started in GRAN SASSO
**H.V. Klapdor-Kleingrothaus**

[ 12] Experimental confirmation of of cascade-type two-sectional blankets concept
**N.V. Zavialov**

# Uncertainty Quantification

**Sunset**, Friday 8:30–10:10

[542] Nuclear Data Uncertainties in 2004: A Perspective
**D.L. Smith**

[249] Revision and Application of Covariance Data Processing Code, ERRORJ
**G. Chiba**

[464] Probabilistic Interpretation of Peelle's Pertinent Puzzle and its Resolution
**K.M. Hanson**

[ 84] Assessment of the Uncertainties Associated with the Optical Model Potential in Evaluations
**E. Bauge**

[312] Covariances for Evaluations Based on Extensive Modelling
**H. Leeb**

## [205] Microscopic Scattering Calculations and Data Analysis in Light Nuclei

Hartmut M. Hofmann

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The Refined Resonating Group Model [1] was modified to allow for realistic NN and 3N-forces. We calculated for the $^4$He compound-system the S-matrix using the realistic two-nucleon potential Argonne V18 and the three-nucleon Urbana IX (UIX) potential. All two fragment channels $p-^3$H, $n-^3$He, and $d-^2$H were taken into account together with approximations for the three- and four-body break-up channels. Using V18 and UIX the binding energies of the fragments and the thresholds were reproduced within 20 keV or better. For the scattering calculation we include all $S$, $P$ and $D$ wave contributions to the $J^\pi = 0^+, 1^+, 2^+, 0^-, 1^-$ and $2^-$ channels. For the V18 alone we allow also for $F$ waves leading to $2^-, 3^-$, and $4^-$ channels. The results are compared either directly to data or, on a partial-wave by partial-wave basis, to a comprehensive R-matrix analysis of a large amount of data in the $^4$He system.

The overall agreement between data and the calculated parameter-free results is quite good. For the V18 alone, the agreement in most cases is much better than in a previous calculation [2] employing a version of the Bonn potential. The partial-wave comparison with the R-matrix analysis yields in many cases perfect quantitative agreement, but also clear-cut differences. On one side these deviations between calculation and data could be used to improve the three-nucleon force. On the other side inconsistencies in the database and regions sensitive to nuclear parameters call for additional or improved data.

Restricting the Gaussian width parameters of the scattering calculation to those independent within the channel-radius of an R-matrix analysis, the R-matrix poles and partial width amplitudes can be calculated and compared directly. We find the properties of the low-lying poles rather insensitive to parameter variations. The channel radii determine an energy region from which on R-matrix poles are abundant and highly dependent on small parameter modifications.

Due to computer-time limitations nuclei above mass number 4 are at the moment not accessible to realistic NN and 3N-forces. For heavier systems only semi-realistic forces are feasible. These forces do no more allow to reproduce the many thresholds by unrestricted variation. Hence, in a scattering calculation artifacts due to this failure cannot be excluded. For the direct determination of R-matrix poles non-orthogonal wave functions, reproducing the various thresholds very well, can be used avoiding these artifacts. First applications of the above treatment to the $^7$Li and $^{11}$B systems are discussed.

1. H.M.Hofmann, in Lecture Notes in Physics 273 (Springer,Heidelberg,1987)

2. H.M.Hofmann and G.M. Hale, Nucl. Phys. **A613**, 69 (1997).

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## [222] Level Density Corrections for Missing and Spurious Levels

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Nuclear level densities are crucial for the calculation of reaction rates and cross sections. Experimental data obtained by direct counting methods are from low-lying discrete levels and from compound nuclear resonances. A key difficulty is that the experiments are never perfect — some levels are not observed and some quantum numbers are misassigned. These are called the missing level and spurious level problems.

For the missing level problem, the standard approach assumes that the underlying distribution is a Porter-Thomas distribution and that the weakest levels are missed. A new approach is based on the measured spacing distributions. Using the principle of maximum entropy, we have obtained a probability distribution for imperfect eigenvalue sequences. The method used to determine the fraction of missing levels is described in a recent paper [1].

For the spurious level problem we use the most striking characteristic of the spacing distribution: level repulsion. The existence of very small spacings is a signature of misassignment. If an experimental

data set has a mixture of states with different quantum numbers, the degree of mixing is reflected in the disappearance of the level repulsion. Extrapolation of the probability distribution to zero spacing provides an estimate of the relative size of the states with different symmetries.

[1]U. Agvaanluvsan, G. E. Mitchell, J. F. Shriner, Jr. , M. Pato, Phys. Rev. C **67** 064608 (2003)

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## [543] Neutron Capture Cross Sections: From theory to experiments and back

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Starting from the recent developments of radioactive ion beams physics to experiments at the CERN spallation neutron source, n_TOF, direct measurements as well as indirect methods of extracting neutron capture cross sections will be reviewed. The theoretical modeling of this basic reaction process is necessary in the widest range of applications, from nuclear data for advanced nuclear technologies to nuclear astrophysics. An outlook of possible developments of the experimental plan for measurements at CERN n_TOF will be presented together with some implications on the theoretical modeling.

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## [91] Recent results on the measurements of the P-odd correlations in the capture of slow polarized neutrons by $^6$Li and $^{10}$B

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Two experiments on the P-odd correlation measurement were carried out at the high intensity polarized cold neutron beam of the PF1B instrument of the ILL reactor, Grenoble, France. The triton emission asymmetry in the $^6Li(n,\alpha)^3H$ reaction and the asymmetry of the emitted $\gamma$-quanta at discharge of the $^7Li$ first excited state populated in the $^{10}B(n,\alpha)^7Li$ reaction were measured. In the experiments a special apparatus and measurement method were used. The preliminary results of the $^6Li$ and $^{10}B$ measurements are $\alpha^t_{PNC} = -(8.1 \pm 3.9)10^{-8}$ and $\alpha^\gamma_{PNC} = -(11.0 \pm 6.6)10^{-8}$, respectively. At the base of first result, the most accurate at present day estimation of the weak neutral current constant has been given: $f_\pi \leq 1.210^{-7}$. The results are discussed.

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## [254] Distribution of prompt neutron emission probability for fission fragments in spontaneous fission of $^{252}$Cf and $^{248,244}$Cm.

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Neutrons emitted in the fission event were measured separately for each complementary fragment in correlation with fission fragment energies. Two high efficiency Gd-loaded liquid scintillator tanks were used for neutron registration. Fission fragment energies were measured using a twin Frisch gridded ionization chamber with a pin-hole collimator. The neutron multiplicity distributions were obtained for each value of the fission fragment mass and energy and corrected for neutron registration efficiency, background and pile-up. The dependencies of these distributions on fragment mass and energy for different energy and mass bins, as well as mass and energy distribution of fission fragments are presented and discussed.

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## [388] Neutron capture cross sections for the Re/Os clock

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The radioactive decay of $^{187}$Re $\rightarrow$ $^{187}$Os ($t_{1/2}$ = 43 Gyr) is suited for dating the onset of heavy element nucleosynthesis. The radio-genic contribution to the $^{187}$Os abundance is the difference between the natural abundance and the corresponding s-process component. This component can be obtained via the well established $< \sigma >_N$ systematics using the neighboring s-only isotope $^{186}$Os, provided the neutron capture cross sections of both isotopes are known with sufficient accuracy.

We report on a new set of experiments performed with a C6D6 detector array at the n_TOF neutron spallation facility of CERN. The capture cross sections of $^{186}$Os, $^{187}$Os, and $^{188}$Os have been measured in the neutron energy range between 1 eV and 1 MeV, and Maxwellian averaged cross sections were deduced for the relevant thermal energies from kT = 5 keV to 100 keV.

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## [49] GENIUS Test Facility for Dark Matter Search Started in GRAN SASSO

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The first four naked high purity Germanium detectors were installed successfully in liquid nitrogen in the GENIUS-Test-Facility (GENIUS-TF) in the GRAN SASSO Underground Laboratory on May 5, 2003. This is the first time ever that this novel technique aiming at extreme background reduction in search for rare decays is going to be tested underground. First operational parameters are presented.

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## [12] Experimental confirmation of of cascade-type two-sectional blankets concept

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Of late years there has been arisen an interest to two-sectional blanket reactors with one-way neutron coupling of the sections (cascade type blankets). These facilities are designed to operate within accelerator-driven energetic and transmutational systems, and being applied, they provide essential reduction of the required capacity of the proton accelerator. There are some theoretical and design works pertinent to cascade type blankets, but no experimental investigations are so far available.

Deeply subcritical systems were under study $k_{eff} \cong 0.6$, which in diverse combinations contained a neptunium sphere of 8.17 cm diameter with the internal cavity of 3.4 cm diameter, layers of uranium-235 (90% concentration rate), layers of moderator, air gaps and cadmium filter. In the center of the neptunium sphere a primary neutron source $^{252}$Cf was placed.

To measure density distributions and total number of fissions of neptunium and uranium nuclei in the systems dielectric track detectors were employed. During the results processing the total number of fissions in each section of the multiplying system was normalized to one neutron emitted by the californium source.

Satisfactory agreement was obtained for the experimental and calculated values of the number of fissions in the assemblies and the factors of cascade multiplication. As the experiment results have indicated, the assemblies under study, in spite of the rather low $k_{eff}$ value, yield considerable cascade multiplication of the number of fissions. For one of the assemblies containing a neptunium sphere the cascade multiplication factor was 2.81.

The experiment results have afforded good corroboration for the theoretical estimates of cascade blanket properties, as well as for the efficiency of neptunium-237 use for providing the sections one-way coupling.

This work was supported by International Scientific and Technological Center (project #909)

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## [542] Nuclear Data Uncertainties in 2004: A Perspective

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Interest in nuclear data uncertainties is growing quite rapidly after having languished for several years. Renewed attention to this topic is being driven by the very practical need for assuring that nuclear systems will be safe, reliable, and cost effective, according to the unique requirements of each specific application technology. Furthermore, interest is also emerging in certain areas of basic nuclear science, such as astrophysics, where, until recently, attention has been focused mainly on uncovering basic concepts and principles rather than on acquiring detailed quantitative knowledge. The availability of fast computers and concurrent development of sophisticated software now enables the available nuclear data uncertainty information to be used more effectively than was the case in earlier years. Unfortunately, the current inventory of requisite uncertainty data is quite limited when measured against these growing demands. Thus, there is a real need to generate more comprehensive and reliable uncertainty data, and to make it readily available within a relatively short period of time in suitable form for use by the computer codes employed for the development and analysis of nuclear systems. This conference contribution discusses some of the key issues that need to be addressed in meeting this demand during the next several years. The many opportunities that will be afforded by the availability of more extensive and reliable uncertainty information, as well as some of the associated pitfalls that need to be avoided, will also be stressed in this contribution.

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## [249] Revision and Application of Covariance Data Processing Code, ERRORJ

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It is important to evaluate an uncertainty of nuclear characteristics in the reactor core analysis field. For such kind of analysis, covariance data of cross sections are essential.

To apply the covariance data for the uncertainty analysis, group-averaged covariance data are necessary. The original ERRORJ code was developed based on ERRORR module in NJOY94.105 to obtain it by K. Kosako in 1999. ERRORJ can treat the covariance data of cross sections including resonance parameters, angular distributions and energy distributions of secondary neutrons which could not be dealt with by the former covariance processing codes.

ERRORJ has been modified in several calculation parts processing the average cosine of elastic scattering angle and the resonance parameters and ERRORJ version 2.2 will be released in near future. The revision of ERRORJ increases its reliability.

The newest ERRORJ was applied into processing covariance in several kinds of nuclear data files, such as JENDL, ENDF/B and JEFF. The processing had been done without problems. There was a large difference in the obtained group-averaged covariance data. We estimated the effect of the difference on uncertainties of nuclear parameters of fast reactor cores by introducing sensitivity coefficients. The results were very different to each other. For example, uncertainty of elastic scattering cross section of iron induces uncertainty on $k_{eff}$ of JOYO MK-III core, which is 1.5%$\Delta k$ for JENDL-3.2 and 0.2% $\Delta k$ for ENDF/B-V. It is important and necessary to discuss further the methodology of the evaluation of the covariance data.

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## [464] Probabilistic Interpretation of Peelle's Pertinent Puzzle and its Resolution

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The confusion surrounding Peelle's pertinent puzzle (PPP) arises in part because of its imprecise statement, which leads to a variety of interpretations and resulting answers, some of which seem implausible. For example, in the PPP specification, it is not stated whether the uncertainties contribute to the measurements in an additive or multiplicative manner. This ambiguity leads to vastly different answers, depending on one's interpretation of the puzzle. In our approach to the PPP problem, we emphasize the importance of basing the analysis on an unambiguous probabilistic model that is consistent with fundamental physical principles. Although the model may be nonlinear and require an iterative solution, its accurate evaluation must yield plausible and justifiable results. We present several contrasting models of how the measurements quoted in the PPP problem could be obtained, and interpret their solution in terms of a detailed probabilistic analysis. We discuss the influence of tacit assumptions that are typically made in data analysis, for example, that of assuming Gaussian distributions for the probability density functions to describe the likelihood of the data.

We conclude by analyzing several data sets that have been used in the past to illustrate the puzzling nature of the answers that can be obtained through application of routine analysis procedures. We show that a precisely-stated model can clarify the approach that needs to be taken to obtain a solution that is consistent with our physical intuition. A suitable approach to analyzing large data sets is described and demonstrated.

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## [84] Assessment of the uncertainties associated with the optical model potential in evaluations.

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In the model-based nuclear data evaluation process, the optical model potential (OMP) plays a central role, especially the entrance channel OMP which determines the reaction cross section that is broken down into individual channels by the statistical model. If enough good quality data is available to calibrate OMP parameters, the uncertainties associated with this OMP are essentially the same as the uncertainties on the experimental data used for parameter adjustment. On the other hand, if not enough data is available, a global OMP must be used, and there should be at least some assessment

of the uncertainties associated with this global OMP. Using the semi-microscopic OMP of (E. Bauge, J.P. Delaroche, and M.Girod, Phys. Rev C **63**, 024607 (2001) ) as a basis for our study, we propagate the uncertainties associated with the adjusted normalization factors of the potential to the calculated quantities, using the Monte-Carlo method. We can thus calculate not only cross sections but also their associated uncertainties in cases when essentially no data is available. The uncertainties on the entrance channel OMP obsevables can then be propagated to the rest of the evaluation process.

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## [312] Covariances for evaluations based on extensive modelling

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There is an increasing demand from the user community for evaluated nuclear data files which include covariance matrices. At present corresponding evaluated files exist only for a small group of isotopes and are almost exclusively based on experimental data up to 20MeV. The planned extension of the energy range of evaluated nuclear data files to about 200MeV requires extensive use of nuclear models. The determination of the covariance matrix associated with model calculations is still an open question.

In this contribution we present a method for the determination of covariances of integral cross sections for model calculations. The method accounts for three types of uncertainties, i.e. the parameter uncertainties, the numerical implementation errors and the model deficiencies. Thus it provides covariance matrices for phenomenological models as well as for almost parameter free microscopic calculations on the same footing. Emphasis is given to a reliable estimate of covariance contributions due to model failures. Based on a well defined mean model error we construct a covariance matrix which satisfies the essential statistical requirements. The covariance contributions due to parameter uncertainties have been evaluated by the usual statistical procedures. Numerical implementation errors depend on the considered observable and the numerical algorithm and must be considered for each case separately.

We apply this method to determine covariances associated with a phenomenological and a microscopic Optical Model calculation for $^{56}$Fe. These covariances are used as a-priori values in a Bayesian update procedure with experimental data in the energy range 20 to 60MeV thus extending the evaluated data file of $^{56}$Fe with covariances. Although the two models are quite different, the error bands overlap essentially even in cases of scarce data which is an indication of the reliability of the proposed procedure. Further applications are in progress.

Work supported by Österreichische Akademie der Wissenschaften, KKKÖ-Project 8/2002.

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# Plenary Session

**Anasazi**, Friday 10:30–11:30

[499] An Eclectic Journey Through Experimental Physics, or How I Learned to Stop Worrying and Love Nuclear Data
**E.B. Norman [Invited]**

[540] The Importance of Nuclear Data to Modern Technology
**J. Ziegler [Invited]**

# Plenary Session / Closeout

Friday 11:30–12:15

## [499] An eclectic journey through experimental physics, or how I learned to stop worrying and love nuclear data

Eric B. Norman

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The databases that are compiled, evaluated, and disseminated by the national and international nuclear data programs are invaluable resources for basic physics research, engineering, medicine, and a host of applied activities. Sometimes this fact is not fully appreciated by either our scientific colleagues or by the funding agencies that pay for the work that is required to produce and maintain this information. Part of the reason for this is that many people are unaware of the breadth of the available data and the ease with which it can be accessed. In this talk, I will illustrate how the ability to rapidly access the broad range of nuclear data has facilitated my own research in fields from searches for double beta decay, to measurements of astrophysical reaction rates, to issues in homeland security. I will also point out places were new data would be especially helpful. In doing this, I hope to persuade even the skeptics that for the benefit of the broad scientific community, it is imperative that the outstanding work of the nuclear data community continue.

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## [540] The Importance of Nuclear Data to Modern Technology

James Ziegler

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Knowledge of accurate nuclear data is essential in solving many of the problems of modern technology. As examples, a discussion is made of the limits of current Electronic Reliability and the "Ship Effect".

The problem of Electronic Reliability has been addressed by R. Baumann, Mgr. of Electronic Reliability for Texas Instruments. He notes that the effects of radiation, especially sea level cosmic rays, is the most important component of digital electronic failure, and its effects surpass all other modes of integrated circuit failure put together. A. Chatila, vice president of Cypress Semiconductor, has said, "Soft errors from ambient radiation are the primary limit on digital electronic reliability. In the era of ubiquitous computing, with interlaced intelligence, constant system crashes from soft fails are black clouds threatening future complexity." The study of the devastating effect of a single neutron on computer systems networks will be reviewed.

The Ship Effect concerns the interdiction of ships to detect nuclear WMD while the ships are still at sea. Swift small boats make radiation sweeps to detect the possible nuclear signature of concealed nuclear devices. The term "Ship Effect" refers to the unexpected phenomenon that very large vessels, especially laden with cargo containers, are natural sources of anomalously high neutron emission. This surprising result is reviewed.

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# Poster A

**Zia**, Monday 15:30–17:30

## Nuclear Data in Astrophysics and Cosmology

61 A neutron source for activation measurements in a stellar spectrum at kT=5 keV
*Michael Heil, Saed Dababneh, Franz Käppeler, Shawn O'Brien, Ralf Plag, Rene Reifarth*

65 Stellar (n,$\gamma$) cross sections of the stable Ne isotopes
*Ralf Plag, Michael Heil, Franz Käppeler, Ausra Juseviciute, Alberto Mengoni, Roberto Gallino*

188 Neutron radiative capture on ultra-magnetized atomic nuclei
*Vladimir N. Kondratyev, Oleg A. Bezshyyko, Ihor M. Kadenko, Vladimir A. Plujko*

220 Measurement of Cross Sections for the $^{63}$Cu$(\alpha,\gamma)^{67}$Ga
*Shamsuzzoha Basunia, Eric B. Norman, Howard A. Shugart, Michelle Dolinski, Brian Quiter*

322 Evaluated (n,$\gamma$) excitation functions and the prediction of the mean GCR particle flux
*Daniel Kollar, Rolf Michel, Jozef Masarik*

352 Measurement of the $^{107}$Ag($\alpha$,$\gamma$) Cross Section
*Coral M. Baglin, Eric B. Norman, Ruth-Mary Larimer, Greg Rech*

374 Measurement of the cross section of (p,$^3$H) reactions in $^{46}$Ti, $^{58}$Ni and $^{90}$Zr
*Francis Bringas, Marcelo T. Yamashita, Iuda D. Goldman, Paulo R. Pascholati, Valdir Sciani*

381 New Evaluations and Computational Infrastructure for Management and Visualization of Nuclear Astrophysics Data
*Caroline D. Nesaraja, Michael S. Smith, Richard A. Meyer, Daniel W. Bardayan, Jeffery C. Blackmon, Kyungyuk Chae, Michael W. Guidry, W. Raphael Hix, Raymond L. Kozub, Eric J. Lingerfelt, Zhanwen Ma, Jason P. Scott*

441 A new systematic determination of fission barriers with the HFB model
*Mathieu Samyn, Stéphane Goriely*

458 NUCLEAR DATA AND NEUTRON CAPTURE NUCLEOSYNTHESIS — A SPECIFIC ASTROPHYSICAL (n, $\gamma$) SCENARIO
*RAMEN K. PARUI*

459 Review of experimental data on alpha induced reactions of some nuclei (Mg-24, Si-28, S-32, Ar-36, Ca-40) in terms of astrophysical applications
*Svetlana A. Dunaeva, Victoriya McLane, Mikchael V. Savin, Sophiya M. Taova*

## [61] A neutron source for activation measurements in a stellar spectrum at kT=5 keV

Michael Heil[1], Saed Dababneh[1], Franz Käppeler[1], Shawn O'Brien[2], Ralf Plag[1], Rene Reifarth[3]

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We report on a measurement of the neutron energy spectrum of the $^{18}$O(p,n) reaction at a proton energy of 2582 keV, just 8 keV above threshold. At this energy the resulting spectrum resembles almost perfectly a Maxwellian neutron energy spectrum for a thermal energy of kT=5.1 keV. Since the neutrons are emitted in a forward cone of 140° opening angle this neutron source can be ideally used for neutron activation measurements similar to the $^{7}$Li(p,n) reaction which is well established for producing a thermal spectrum at kT=25 keV. Measured neutron capture cross sections at kT=5.1 keV can be safely extrapolated to kT=8 keV which is characteristic for the dominant neutron exposure, producing the main s-process component in thermally pulsing low mass AGB stars. As a first application the Maxwellian averaged capture cross section of $^{138}$Ba was measured.

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## [65] Stellar (n,$\gamma$) cross sections of the stable Ne isotopes

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Stellar neutron capture on neon isotopes is important for a number of astrophysical quests, i.e. for the interpretation of abundance patterns in presolar material or with respect to the *s*-process neutron balance in red giant stars. New resonance studies have been performed with the R-Matrix code SAMMY using experimental data in the keV range which had not been fully analysed before. The analysis included the consistent treatment of possible interferences in the resonant part. Theoretically calculated direct capture contributions, which are important for these light nuclei, were normalized by means of improved thermal cross sections. With these results the stellar rates could be determined for the relevant temperature range from kT = 1 keV to 100 keV. Comparison with previous data shows that these cross sections have been significantly overestimated.

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## [188] Neutron radiative capture on ultra-magnetized atomic nuclei

Vladimir N. Kondratyev, Oleg A. Bezshyyko, Ihor M. Kadenko, Vladimir A. Plujko

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During past decade the observations of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) brought numerous evidences in support of a 'magnetar' concept suggesting enormous magnetic fields in supernovae and nascent neutron stars with a strength ranging up to $B \sim 10^{17.5}$ G (see, e.g., [1] and refs.therein). Assertion of a possibility of ultra-magnetized stellar media rises the question of the effect of magnetic field in nuclide transformations. In this contribution we consider an example of $(n, \gamma)$ reactions involving ultra-magnetized atomic nuclei.

Employing the Hauser-Feshbach statistical approach the important magnetic field effects in neutron radiative capture are argued to originate from modifications of nuclear level densities and $\gamma$-transition energies. The relationship between these contributions as well as the sensitivity to approximations are illustrated on schematic examples of neutron capture by neutron-odd nuclei which yield exit channel even-even nuclei corresponding to $^{44}$Ti and $^{56}$Ni.

As shown the magnetic energy leads to re-distribution of spin-states in out-channel. The largest contribution of resulting zero-spin nucleus at zero field sharply vanishes with increasing field strength, while the population of the highest allowed spin-states grows. This results in nearly constant cross section in weak field limit. In magnetic fields of large strengths such highest spin-states of final nuclei give predominant contribution to the total cross section because of large extra-energy in $\gamma$-channel. Strong

magnetic field results in considerable enhancement of radiative $n$-capture process. Such a magnetocatalysis is considerably stronger for larger values of nuclear $g$-factor. The magnetic change of level spacing reflects magnetic effect in nuclear structure [2] and gives rise to oscillations of $n$-capture cross section around an enhancement caused by magnetic energy. Contribution of such oscillations is particularly important for relatively small absolute values of $g$-factors. The magnetic effects in level spacing gives rise to considerably different cross section ratios for $^{56}$Ni and $^{44}$Ti nuclei. For the case of product-nucleus $^{56}$Ni, with closed shell at zero-field, $n$-capture process displays stronger enhancement, while for $^{44}$Ti the reaction can be suppressed at weak fields.

1.C. Thompson and N. Murray, ApJ **560**, 339 (2001);
2.V.N.Kondratyev, Phys. Rev. Lett. **88**, 221101 (2002); J. Nucl. Sci. Tech. Suppl. **2**, 550 (2002); J. of Nucl. and Radiochem. Sci. **3**, 205 (2002)

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## [220] Measurement of Cross Sections for the $^{63}$Cu$(\alpha,\gamma)^{67}$Ga

Shamsuzzoha Basunia[1], Eric B. Norman[1], Howard A. Shugart[2], Michelle Dolinski[2], Brian Quiter[2]

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As has been pointed out in a number of recent papers (Ref. 1 and references therein), there are a number of astrophysical environments where charged-particle induced reactions on nuclei heavier than iron may play important roles. There are theoretical estimates of the cross sections for these kinds of reaction. However, until recently there has been little experimental data with which the theoretical estimates can be compared. We have measured cross sections for the $^{63}$Cu$(\alpha,\gamma)^{67}$Ga reaction for 5-8 MeV alpha particles using an activation technique. Stacks of four $^{nat}$Cu metal foils of 1 mg/cm2 thickness and one $^{nat}$Ti foil of thickness 2.7 mg/cm2 were bombarded with alpha beams from the 88-inch Cyclotron at LBNL. The titanium foil was used for checking the current integration by measuring and comparing with the known $^{48}$Ti($\alpha$,n) $^{51}$Cr cross sections (2). Following each irradiation, the copper targets were counted immediately using an HPGe detector to observe $^{68}$Ga, produced through the $^{65}$Cu($\alpha$,n) $^{68}$Ga reaction. The cross section for this reaction was measured and compared with data reported by Stelson et al. (3) as a check of the overall experimental technique. Later, all the copper foils were counted for longer periods of time to observe $^{67}$Ga using another HPGe detector located inside LBNL's Low Background Facility. $^{63}$Cu$(\alpha,\gamma)^{67}$Ga cross-sections were determined. The results of our measurements will be compared to modern Hauser Feshbach calculations.

**References**

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2. A. J. Morton, S.G. Tims, A.F. Scott, V.Y. Hansper, C.I.W. Tingwell, and D.G. Sargood, Nucl. Phys. A 537 (1992) 167.
3. P.H. Stelson and F.K. McGowan, Phys. Rev., 133 (1964) B911.

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## [322] Evaluated (n,$\gamma$) excitation functions and the prediction of the mean GCR particle flux

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For an accurate modeling of the production rates of cosmogenic nuclides in extraterrestrial matter the availability of reliable excitation functions is essential. For the (n,$\gamma$) reactions there exist excitation functions for most target isotopes relevant in the cosmic ray applications within the nuclear evaluated data files.

Here we report on the calculations of the n-capture produced cosmogenic nuclides $^{36}$Cl, $^{41}$Ca, $^{60}$Co, $^{59}$Ni, $^{80}$Kr, $^{82}$Kr, and $^{129}$I in stony meteorites. The transport of the galactic cosmic ray (GCR) particles was simulated using the LAHET Code System [1,2]. The excitation functions were taken from the ENDF/B-VI [3] and JEF-2.2 [4] libraries. The results show that for some nuclides there are cosiderable

differences between production rates calculated using the excitation functions from the two libraries (up to 30%).

From the comparison of calculated and measured production rate depth profiles of cosmogenic nuclides the value of the mean GCR particle flux can be determined. For the (n,$\gamma$) reactions this was done by comparing the calculations to the $^{41}$Ca depth profile from the Apollo 15 drill core [5] leading to the value of 2.99 cm$^{-2}$ s$^{-1}$ at meteoroid orbits. This value significantly differs from the values obtained from similar models for spallation production 4.8 [6] and 4.06 cm$^{-2}$ s$^{-1}$ [7]. The reasons for this difference are not clear and further investigation is needed especially with respect to the excitation functions for both (n,$\gamma$) and spallation reactions.

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## [352] Measurement of the $^{107}$Ag($\alpha$,$\gamma$) Cross Section

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Cross sections have been measured for the $^{107}$Ag($\alpha$,$\gamma$)$^{111}$In reaction at several energies between 8 and 12 MeV. This reaction is of interest because it can provide a check on calculations of low energy ($\alpha$,$\gamma$) cross sections required for stellar nucleosynthesis predictions. Stacks of natural Ag foils of 1 micron thickness and 99.97% purity were bombarded with a $^{4}$He$^{+}$ beam from the LBNL 88" cyclotron. Following bombardment, the yields of the 151-keV and 245-keV photons produced in the 2.805 d electron-capture decay of the $^{111}$In product nucleus were measured off-line. The Ag targets were interleaved with 99.6% purity, 6 micron thick natural Ti foils so that known cross sections for the $^{48}$Ti($\alpha$,n)$^{51}$Cr reaction could be used to check the accuracy of the beam current integration. For any given beam energy, beam energy degradation in the foils resulted in lower effective bombarding energies for successive foils in the stack, enabling measurements to be made for several energies per irradiation. The measured cross sections will be compared with published cross sections obtained from Hauser-Feshbach calculations.

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## [374] Measurement of the cross section of (p,$^{3}$H) reactions in $^{46}$Ti, $^{58}$Ni and $^{90}$Zr

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We have determined the cross section of the reactions $^{46}$Ti(p,$^{3}$H)$^{44}$Ti, $Q = -14.238$ MeV and $T_{1/2} = 62.3(5)$ y; $^{58}$Ni(p,$^{3}$H)$^{56}$Ni, $Q = -13.984$ MeV and $T_{1/2} = 6.10(2)$ d; $^{90}$Zr(p,$^{3}$H)$^{88}$Zr, $Q = -12.805$ MeV and $T_{1/2} = 83.4(3)$ d, for energies up to 30 MeV.

The experimental method used had consisted in the measurement of the residual activities of the reaction products by the simple gamma spectroscopy, following, when necessary, the decay of the half-life. Characteristics gamma-rays and half-lifes allows an unambiguous determination of the related activities. Parameters like target thickness, beam energy and current, were carefully determined due to the fast variation of the cross section in the energy interval considered.

The irradiations were performed at the Cyclone-30 cyclotron of the Institute for Nuclear and Energetic Research (IPEN). The targets were settled in the usual way of stacked-foils, with thin foils of natural Ti, Ni and Zr plus sheets of Al for energy degradation. On each targets, two thin foils of Cu were placed for beam energy and current monitoration. The gamma spectra were acquired with a HPGe germanium detector with energy resolution better than 1.69 keV for the 1332 keV transition of $^{60}$Co. Special attention was paid to the detector energy and efficiency calibration.

The cross section values obtained were compared with published values of other authors. Also, theoretical calculation with well known theoretical model including equilibrium and pre-equilibrium emissions were done to test the capability of these models to predict experimental results in the energy range and reaction considered such as their usefulness for new experimental design.

All the studied reactions have great astrophysical interest. All results were consistent with the previous known data, and contributes to fill an energy region (near the reaction threshold) where it is noticeable the scarce data in many cases, in spite of been relatively very well known reactions at higher energies.

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## [381] New Evaluations and Computational Infrastructure for Management and Visualization of Nuclear Astrophysics Data

Caroline D. Nesaraja[1], Michael S. Smith[2], Richard A. Meyer[3], Daniel W. Bardayan[2], Jeffery C. Blackmon[2], Kyungyuk Chae[4], Michael W. Guidry[4], W. Raphael Hix[5], Raymond L. Kozub[6], Eric J. Lingerfelt[5], Zhanwen Ma[4], Jason P. Scott[5]

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Recent measurements with radioactive beams at ORNL's Holifield Radioactive Ion Beam Facility (HRIBF) have prompted the evaluation of the structure and reactions of unstable nuclei that play an important role in stellar explosions. We will present the latest results of these evaluation efforts. To determine the astrophysical impact of these evaluations and other new nuclear physics results, it is vital to rapidly and accurately process and incorporate them in astrophysics models. To this end, we are developing a suite of computer programs that simplify and standardize the generation, parameterization, and visualization of reaction rates, and ease their incorporation into databases used for element synthesis calculations. The codes are accessible with a WWW interface through www.nucastrodata.org, a site which also hyperlinks all available nuclear data sets relevant for nuclear astrophysics studies. Features of the program suite and future developments will be presented.

* ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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## [441] A new systematic determination of fission barriers with the HFB model

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Under certain hydrodynamical conditions, the r-process of nucleosynthesis may produce very neutron-rich fissioning nuclei for which no experimental data are known. Fission barriers and rates are therefore important inputs for the r-process, especially concerning superheavy nuclei up to the N=184 magic number. So far, extended tables of fission barriers have been constructed in the microscopic-macroscopic framework of the droplet model, and in the Extended Thomas-Fermi plus Strutinsky Integral (ETFSI) method. The ETFSI method is an approximation to the Hartree-Fock method and includes pairing using the BCS equations. It is however known that pairing correlations and shell effects play a crucial role in exotic nuclei produced by the r-process, for which a more microscopic model may be more appropriate.

We compare experimentally known fission barriers with those calculated using the constrained Skyrme-Hartree-Fock (SHF) method in a 3-dimensional deformation space. The pairing is included either in the BCS approximation or in the Bogoliubov plus particle number projection scheme. Different Skyrme forces fitted to all available nuclear masses given by the Audi and Wapstra compilation are considered. The energy surfaces are analysed using the flooding method, a necessary tool if more than two dimensions are spanned.

The accuracy and reliability of a large-scale SHF fission-barrier calculation, i.e. for about 2000 nuclei of astrophysical interest, is discussed.

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## [458] NUCLEAR DATA AND NEUTRON CAPTURE NUCLEOSYNTHESIS — A SPECIFIC ASTROPHYSICAL (n, $\gamma$) SCENARIO

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The physics of stellar Neutron capture processes (s-process or r-process) is deeply rooted in numerical data which helps us for better understnding the astrophysics of these two processes. In this paper an attempt has been made to explain why nuclear data is the most reliable input data for handling the astrophysical problems, in particular (n,$\gamma$) reaction scenario for dealing with the stellar s-process and r-process unsolved problems.

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## [459] Review of experimental data on alpha induced reactions of some nuclei (Mg-24, Si-28, S-32, Ar-36, Ca-40) in terms of astrophysical applications

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Alpha induced reactions play an important role in the helium burning stage of stars, novae, and supernovae. These reactions are basic to the CNO and Al-Mg cycles, and also to the production of neutrons producing S and R processes occurring in stars. Thus, the availability of cross section data for these reactions is a prime need for the study of nuclear interactions taking place in stars.

The present report gives a detailed analysis of experimental works and a review of alpha-induced reaction cross sections data of five alpha-alpha nuclei, Mg-24, Si-28, S-32, Ar-36 and Ca-40, for incident alpha energy up to 20 MeV.

These data have been compiled as part of an international collaboration, funded in part by the Civilian Research & Development Foundation, and are available in the EXFOR databases.

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# Poster A

**Zia**, Monday 15:30–17:30

# Nuclear Data Evaluations, Data Testing, and Dissemination (I)


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## [26] Photonuclear Reactions: Systematical Disagreements, Methods of Their Overcoming and Physical Consequences

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Majority of photonuclear reaction cross section data has been obtained in experiments using electron bremsstrahlung and quasimonoenergetic photons produced by annihilation in flight of relativistic positrons, many last kind data obtained at Livermore (USA) and Saclay (France). Significant discrepancies between photonuclear reaction (both total and partial) cross sections obtained in various experiments have been discussed /1 – 4/. It was found out that as a rule total photoneutron reaction cross sections obtained at Livermore differ (being smaller in amplitude) from that of other laboratories: Livermore total photoneutron (g,xn) reactions cross section absolute values must used being multiplied /3/ by 1.12.

Additionally it was found out /1/ that disagreements of partial reactions (g,n) and (g,2n) cross sections, obtained at Livermore and Saclay using neutron multiplicity sorting procedure are much more ($\sim 30 - 40$ %) and as a rule have opposite directions. These disagreements were interpreted as the result of difference of neutron multiplicity sorting procedures used: at Saclay incorrect transmission of the part of (g,2n) reaction cross section into the (g,n) reaction cross section took place. The special method /1, 4/ was used to move the data into consistence. Its idea is that correspondent "false" part of (g,n) reaction cross section is recalculated and transmitted back into (g,2n) reaction cross section.

Joint analysis of the (g,xn), (g,n) and (g,2n) reaction cross section data obtained at both laboratories mentioned was carried out /4/ for 19 (for 7 – at first) nuclei $^{51}$V, $^{75}$As, $^{89}$Y, $^{90}$Zr, $^{115}$In, $^{116,117,118,120,124}$Sn, $^{127}$I, $^{133}$Cs, $^{159}$Tb, $^{165}$Ho, $^{181}$Ta, $^{197}$Au, $^{208}$Pb, $^{232}$Th, $^{238}$U and evaluated consistent data were obtained.

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The results of joint analysis and correction of partial photoneutron reactions (g,n) and (g,2n) cross sections for 19 nuclei $^{51}$V, $^{75}$As, $^{89}$Y, $^{90}$Zr, $^{115}$In, $^{116,117,118,120,124}$Sn, $^{127}$I, $^{133}$Cs, $^{159}$Tb, $^{165}$Ho, $^{181}$Ta, $^{197}$Au, $^{208}$Pb, $^{232}$Th, $^{238}$U obtained using quasimonoenergetic photons from relativistic positron annihilation in flight at Livermore (USA) and Saclay (France) /1 - 3/ were used for study of balance between photoabsorption integrated cross section values and dipole sum rule estimations 60NZ/A. That correction was forced by incorrect neutron multiplicity sorting procedure used at Saclay. It means that correspondent "false" part of (g,n) reaction cross section was recalculated and transmitted back into (g,2n) reaction cross section. The main result of such kind correction was that Saclay s(g,2n) corrected became significantly larger. Because s(g,abs) = s(g,xn) - s(g,2n) + s(g,p) it must became noticeably ($10 - 30$%) smaller. Therefore large extra integrated cross section values sint(g,abs) $\sim 1.3 - 1.5$ 60NZ/A (MeV x mb) obtained in many Saclay experiments /for example, 4 - 7/ became doubtfully being all due to effective mass of nucleon changing because of the effect of exchange forces. Corrected photoabsorption integrated cross sections are presented for all 19 nuclei studied.

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Calculations of electromagnetic dissociation cross sections of ultrarelativistic heavy ions are generally based on approximations and extrapolations of the experimental data on photon-induced nuclear reactions. In particular, there exists a proposal /1/ to monitor the beam luminosity in ultrarelativistic heavy-ion colliders /2, 3/ by measuring neutron emission rates in mutual electromagnetic dissociation of colliding nuclei. The discrepancy between the photonuclear data obtained in different experiments deteriorates /4/ the accuracy of the method, which rests on calculated dissociation cross sections.

Basing on a systematic analysis /5/ of the experimental photoneutron reaction cross sections, the reasons for such discrepancy were investigated, and a means of eliminating the disagreement were proposed. By confronting calculation results with the recent experimental data on electromagnetic dissociation of 30 A GeV $^{208}$Pb, it was demonstrated /6/ that the obtained evaluated cross sections of (g,n) and (g,2n) reactions, when used to adjust the model, make possible to improve the reliability of predicted electromagnetic dissociation cross sections.

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The MSU SINP Centre for Photonuclear Experiments Data (Centr Dannykh Fotoyadernykh Eksperimentov - CDFE) is specialized on both compilation, processing and evaluation of photonuclear data and development of powerful and flexible relational nuclear databases (LINUX, MySQL, Apache, CGI) including all nuclear reactions and nuclear spectroscopy data /1/.

The "Nuclear Reaction Database (EXFOR)" included many photon, neutron, charge particle and heavy ion reaction data was improved (in cooperation with CAJaD, Russia) significantly by producing of advanced Search Engine giving to one possibility to search data in so called "inverse geometry" (any "incident particle (a) and target nucleus (b)" combinations - "a + b" and "b + a" - and correspondent recalculation of energy values).

New completely relational nuclear spectroscopy database was developed (http://depni.sinp.msu.ru/cdfe/services/ensdfr.html) as improved version of database NESSY (New ENSDF Search System) /1/; it includes practically all data from the ENSDF, has new flexible and powerful Search Engine, and additionally gives to one possibility to receive any part of source file; direct connection to references from the NSR (Nuclear Structure References) file is now under construction. Till now new "Nuclear Physics Publications ("NSR" Database)" based on the NSR file (USA NNDC) was also realized as new relational database (http://depni.sinp.msu.ru /cdfe/services/nsr/Search_form.shtml).

"Calculator for Nuclear Reaction Threshold and Energy Values" (http://depni.sinp.msu.ru /cdfe/muh/calc_thr.shtml) was produced using the nucleus mass data /2/ from database "Nuclear Ground State Parameters" - both threshold and energy values can be cumfortably calculated for any reaction with definite incident particle (g-quantum, neutron, charged particle, ...) and any combinations of outgoing particles.

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## [28] ARE QUASIMONOENERGETIC ANNIHILATION PHOTONS ENOUGH MONOENERGETIC REALLY?

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Using the method of reduction /1/ reasons of the well-known systematic discrepancies between results of photonuclear experiments using different photon beams were investigated in details for $^{18}$O$(\gamma, n)$ $^{17}$O /2/, $^{63}$Cu$(\gamma, n)$ $^{62}$Cu /3/, $^{197}$Au$(\gamma, xn)$ /4/ reaction cross sections. For the first time evaluated data were obtained for all three steps of difference procedure (Ye+(Ej) - Ye-(Ej) = Y(Ej) sigma(k)) typical for experiments with quasimonoenergetic photons from annihilation in flight of relativistic positrons (QMA). Clear intermediate structure resonances were found out /5/ (for $^{63}$Cu and $^{197}$Au as distinct from /3, 4/ results) in cross sections evaluated at the same energy resolution for each experiment step (obtained separately from yields Ye+(Ej) and Ye-(Ej) for reactions induced by positrons and electrons and difference Y(Ej)). GDR structure was compared to that obtained in bremsstrahlung experiments, good agreement was revealed. Inverse operation of evaluated cross sections smoothing gave the real QMA-result energy resolution several times worse (1.3 MeV for /3/ and 1.6 MeV for /4/) than estimated before.

Results obtained mean that typical subtraction procedure of QMA-experiments makes difficult noticeably the estimation of energy resolution really achieved in experiment. That leads to significant missing of the information on reaction cross section structure – as a rule QMA-cross sections are significantly over-smoothed. But information lost can be restored by additional data processing using the method of reduction or analogous ones.

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## [45] Incomplete and complete fusion processes in some heavy ion induced reactions

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Some Heavy ion induced reactions were studied using heavy ion beams obtined from Pelletron of Nuclear Science Centre , New Delhi, India. Oxygen and Carbon ions were accelerated at the energy around 80 Mev. Several reactions induced by these heavy ions were studied in various targets. Stacked foil activation technique was used in this study.The measured cross sections were compared with calculated cross-sections using different computer codes. The large difference in the measured and calculated cross sections is due to incomplete fusion of incident projectile. Experiments were also performed for confirmation of ICF. For this the measurements of forward recoil range were done. The study of recoil range gave a direct signature of Incoplete fusion of heavy ions. The result confirms breakup of incident heavy ions.

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## [74] U-Th fuel cycle neutron data

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Neutron data files of main nuclides of U-Th fuel cycle: $^{232}$Th, $^{232}$U, $^{233}$U , $^{234}$U, $^{231}$Pa and $^{233}$Pa are evaluated based on a full-scale Hauser-Feshbach theory, the basic constraint is the observed fission cross section description from ∼keV to 20 MeV. Direct excitations for the ground state band, $\beta(\gamma)-$vibration ($K^\pi = 0^+$, $2^+$) as well as octupole ($K^\pi = 0^-$) band levels were calculated within coupled channels approach. Extended recently measured database on $^{238}$U inelastic scattering contributed to fixing the model parameters. A model of soft, deformable rotator is used for the description of the collective vibrational-rotational states of even-even U and $^{232}$Th. Collective levels of $^{238}$U, $^{232}$U, $^{234}$U and $^{232}$Th for excitations within a pairing gap were identified. Combined analysis of collective levels structure and differential scattering helps to assign the nature of vibrational bands and to define relevant deformation parameters. Levels of $K^\pi = 0^-$ band are defined by octupole deformation parameter $\beta_3$ and parameter $\mu_\xi$ of softness to the octupole vibrations. When angular distribution $^{238}$U data are fitted with $\beta_3-$parameter, level positions are kept unaffected with softness parameter $\mu_\xi$. Experimental cross section data for the groups of octupole band levels of $^{238}$U helped to define $\beta_3$- and $\mu_\xi$-values, the former are adopted for $^{232}$Th and other U nuclei. Levels of second and third $K^\pi = 0^+$ bands are classified as quadrupole transversal $\gamma$- vibrations or longitudinal quadrupole $\beta$- vibrations. Both are defined by $\mu_\beta$ and $\mu_\gamma$, softness parameters to respective vibrations. Anomalous rotational $K^\pi = 2^+$ $\gamma$- band levels are defined by non-axiality parameter $\gamma_o$ which is correlated with different positions of $K^\pi = 2^+$ levels in $^{238}$U, $^{234}$U, $^{232}$U and $^{232}$Th. The rigid rotator optical model potential is also obtained. Prompt fission neutron spectra (PFNS) were calculated with the model [1], validated in case of $^{238}$U and $^{232}$Th PFNS data. Basically that is a "two-fragment" model, which takes into account contribution of neutrons, emitted in (n,xnf) reactions and reproduces their dependence on the target nuclide fissility.

Average unresolved resonance parameters, fast neutron cross sections, angular distributions and secondary neutron spectra differ very much from previous evaluations.

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## [161] ON WEIGHTING MULTIGROUP CROSS SECTIONS

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Media in reactors contain in general many heavy resonant nuclides. To prepare multigroup cross sections for these nuclides, we often, consider an infinite homogeneous medium containing all these nuclides in order to take into account resonance self-shielding and mutual shielding effects. Following the Livolant-Jeanpierre formalism (1), we first determine the fine flux structure by solving the neutron slowing down equation in an infinite homogeneous medium for point wise neutron energy, then we use the obtained fine flux as a weighting function to evaluate multigroup cross sections. Handling such calculation is simple for few resonant nuclides, but it becomes a tedious task fore a large number of resonant nuclides. That requires a huge computer capacity and a large computational time.

In the present work, we propose a simple model to do these calculations with a large reduction of both calculation time and necessary computing time. Basically only one fictitious heavy resonant nuclide "Equivalent Nuclide" is used in the model, to do the calculations of the appropriate weighting function, instead of all the actual resonant nuclides however is their number. The "Equivalent Nuclide" characteristics are directly deduced from those of the actual ones.

The iterative method (2) is used to solve the neutron slowing down equation in order to determine the fine flux which is used as a weighting function for the multigroup cross sections. The model validation has been done for both continuous neutron energy representation and multigroup approximation in the [2.77eV - 676.45eV] and [1.0E-5eV - 2MeV] energy intervals . We have found that our model conserves the reaction rates with a high accuracy and saves more than 82% of the computation time in cases of five heavy resonant nuclides. That leads also to a huge reduction of the necessary computer memory to do the same calculations.

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## [164] R-matrix Analysis for Improvement of the International Standard Cross Section

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This report will introduce:

1. Our R-matrix Analysis Code RAC, which has a full implementation of the error propagation law and several approaches for processing uncertainty of data, has the identical calculation precision with EDA (LANL) and SAMMY (ORNL), has the ability to analyze all kinds of observable existing in one (or two) compound nucleus system (same as EDA), and has many special functions designed for producing standard cross section of light nucleus.

2. The error propagation features of R-matrix model fitting for several light nucleus systems has been studied systematically with RAC. The propagation of covariance depends on the intrinsic features of R-matrix parameters and the error distribution of data. The standard error propagation coefficient P can be expressed by a very simple experience formula. The medium energy range component of systematic error plays very important function for error propagation.

3. The analysis of $^{7}$Li system and $^{11}$B system with RAC separately. The result of 7Li system has been used in the test combining with the result of GMA to produce the standard cross section 6Li (n, t). The standard errors and covariance of combining fit have got much improvement than the quoted values in ENDF/B6. There are some principal difference between the results of RAC and EDA, and the causes for bring out the difference are being studied.

4.The analysis of $^{7}$Li system and $^{11}$B system with RAC simultaneously. It is done by using the data base of $^{7}$Li system, the data base of $^{11}$B system, and the relative data about $^{6}$Li(n,t)/$^{10}$B(n,$\alpha_0$) and $^{6}$Li(n,t)/$^{10}$B(n,$\alpha_1$). This new evaluation procedure can produce more precise and consistent result for standard cross section.

5. Several approaches for processing uncertainty of data are studied systematically. e. g., full implementation of the error propagation law; splitting the full uncertainty at statistical uncertainty and normalization uncertainty. For a given simulation data sets of $^{7}$Li system, the primary result show that the calculated covariance matrixes of $^{6}$Li(n,t) are different. The causes for bring out the differences are explained in detail.

6. How about the positive definiteness of the result obtained by using RAC. The method to improve the positive definiteness is studied.

7. The possibility for the occurrence of PPP in R-matrix analysis. We have searched the causes for the occurrence of PPP in GMA, and found the some main causes do not exist in our R-matrix analysis; the systematical calculations show that there is not this possibility for the occurrence of PPP in our R-matrix analysis.

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## [170] The Study on the Methods for Eliminating PPP

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This report will introduce:

The inter-comparison for all proposed methods to eliminate PPP by deal with a data base (refer to Table 1); a new and the best method to eliminate PPP: Selectively making suitable correction for systematic errors according to the relative extent of discrepancy.

The causes for PPP include: there are not such data which restrict each other; there are some data points with larger discrepancy; the systematic errors are relatively too larger; the errors are quoted in percentage; the grid format about energy.

In Table 1, the Rel-Cs and Rel-Cov refer to averaged calculated cross section and covariance, the 'We-Av' refers to the weighted averaged values, L-PPP refers to lower PPP, H-PPP refers to higher PPP. All proposed methods are effective to eliminate PPP, but the opinion as follow is presented for discussing. The evaluation procedure should be a very objective procedure. Usually the experimenters have credible information to quote the statistical errors, it should not be changed if have not special new evidences; if it is in term of percent, the denominator must be experimental values, not the unknown estimate values. Usually it is hard to quote the systematic errors exactly; to change systematic errors is reasonable and acceptable in evaluation procedure.

The Cox-Box transform changes both all data and errors, it's hard to be accepted; In 'Chiba' method the absolute errors of data are obtained by multiplying the middle estimate values with relative errors, all statistical errors are changed, in fact the same errors are quoted to every datum at one energy, this is 'over-correction', it is hard to get consensus too. But, the Chen's method –'to selectively make suitable correction for systematic errors according to the relative extent of discrepancy' – just making a little correction (about 12%) for few systematic errors can get the best results. It seems more reasonable and should be considered to use at first.

Table 1 Inter-comparison for proposed methods for eliminating PPP

| Title | Chi-S. | Rel-Cs | Rel-Cov | Processing of data and error |
|---|---|---|---|---|
| 1 We-Av | 3.703 | 0.9897 | 0.140 | neglecting non-diago. eleme.of cova. matrix |
| 2 L-PPP | 11.11 | 0.8991 | 1.000 | er=re-est-(mea/est)=re-mea; no any change |
| 3 Chiba | 4.027 | 1.0043 | 1.115 | er = re - est; all errors are changed |
| 4 Zhao. | 4.017 | 1.0040 | 1.098 | er = re - wea; all errors are changed |
| 5 Log | 3.940 | 1.0020 | 1.113 | all cross sections and errors are changed |
| 6 Cox | 4.220 | 1.0104 | 1.132 | all cross sections and errors are changed |
| 7 Chen | 3.758 | 0.9907 | 1.055 | only change few systematic errors |
| 8 H-PPP | 11.31 | 1.130 | 1.000 | er=re-est-(est / mea); opposite to L-PPP |
| 9 RAC | 3.379 | 1.0000 | 0.971 | no any change |

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## [172] Status of the Photonuclear Data Library for CINDER'90

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Recently a renewed interest in photonuclear processes has appeared. It is motivated by a number of different applications where progress in high intensity electron accelerators was awaited. These applications include electron/photon accelerators, shielding studies, radioactive nuclear beam production, transmutation of nuclear waste, intensive neutron sources for material irradiation and ToF facilities, non-destructive characterization of waste barrels, detection of nuclear materials via photo-fission, etc.

Major problems in performing some modeling or optimization studies of above applications are the lack of photonuclear data for corresponding cross sections despite huge efforts of the IAEA: data are available only for 164 isotopes. In addition, no complete material evolution code including photonuclear reactions is available at the moment. For this reason, in a close collaboration with the LANL, we have been working on the development of a new photonuclear activation data library to be included into the CINDER'90 evolution code (LANL). The energy range of incident photons is between 0 and 25 MeV, and an extension of the present activation library up to 150 MeV is planned in the future.

The following photonuclear library construction strategy was chosen:
a) we use the IAEA evaluations for the major 164 isotopes;
b) the latest version of the ALICE code (HMS-ALICE) written by M. Blann is employed to complete the library up to 600 isotopes;
c) in some particular cases new evaluations with the GNASH code are performed (e.g., U-235, Pu-239, Np-237, Am-241);
d) the GSI fission-evaporation code is used to provide the photo-fission fragment distributions.

The accuracy of the calculated and evaluated cross sections is assessed through comparisons with experimental data when available. A companion paper describes developments and testing of the GSI fission-evaporation code for photon induced fission including delayed neutron emission.

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## [175] JENDL Photonuclear Data File

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Nuclear data for photonuclear reactions are required in the field of shielding design of high-energy electron accelerators and high-energy gamma-ray therapy. In the former field, it is highly desirable to perform accurately shielding design of an accelerator building in order to thin the shielding walls as much as possible. In high-energy electron accelerators, the shielding designers mainly analyzed behavior of electrons and bremsstrahlung photons until now. It is, however, clear that neutrons from photonuclear reactions by the bremsstrhalung photons must be also considered for the purpose of precise estimation of the influence of secondary radiations. In the latter field, it is also important to estimate dose from photo-neutrons in order to avoid undesirable irradiation. From these demands for the photonuclear data, a working group on nuclear data evaluations for photonuclear reactions has been organized under an activity in Japanese Nuclear Data Committee (JNDC). From a survey of many literatures, we reached the conclusion that it is difficult to construct the photonuclear data file if we adhere to evaluation method to use measured cross sections only, since there are not sufficient experimental data necessary for the evaluation. For instance, there scarcely exist energy spectra and double-differential cross sections (DDX) for emitted particles which were measured using quasi mono-energetic gamma-rays. We were therefore proceeding the evaluation work with the help of theoretical calculation based on statistical nuclear reaction models. The photonuclear cross sections that are to be contained in the forthcoming data file are as follows: photoabsorption cross sections, yield cross sections and DDX for photoneutrons, photoprotons, photodeuterons, phototritons, photo-3He-particles and photoalpha-particles, isotope production cross sections. For the actinide nuclides, physical quantities related to photofission reaction are also included. The maximum energy of incident photons is 140 MeV because the evaluation work becomes very hard once the pion production channel opens.

The JENDL Photonuclear Data File is planned to be constructed using ENDF-6 format and to be released as soon as possible after review processes. Now we have compiled the photonuclear data for 68 nuclides from H-2 to Np-237.

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## [208] The JEFF-3.0/A Neutron Activation File - New features, validation and usage

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JEFF-3.0/A, as the ENDF-6 format conversion of EAF-2003, contains neutron-induced cross sections for 98 elements, 774 different target nuclei, including first (m) or second (n) isomeric states, from $^{1}$H to $^{257}$Fm. In total 12617 reactions below 20 MeV are included. As a single ENDF-6 formatted file, JEFF-3.0/A can be seamlessly used by evaluators, codes and applications worldwide. Using the data, such codes allow all the target nucleus states, the incident and emitted particles (i.e. charged particles, gas production) as well as the residual nucleus states, to be calculated as a function of time. The format chosen for the JEFF-3.0/A file uses reaction cross sections (MF-3) or cross sections (MF-10) and multiplicities (MF-9) for capture channels. This layout allows 23 open reaction channels per nucleus with the MAT numbers assigned following a strategy where the MAT for isotopes increase in steps of three, allowing for the ground and two metastable states. Having the data in ENDF-6 format allows the ENDF suite of utilities and checker codes to be used alongside many others utility, visualizing or even processing codes.

Based on the EAF activation file used for many applications from fission to fusion, including dosimetry, inventories, depletion-transmutation and geophysics; JEFF-3.0/A takes advantage of four generations of EAF files. Extensive benchmarking activities on these files provide feedback and validation from integral measurements. These, in parallel with detailed differential graphical analysis based on EXFOR have been applied, stimulating new measurements where possible and significantly increasing the quality of this activation file. The next step is to include uncertainty data for all open channels present in the file.

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## [259] Proton Production Cross Sections for Reactions Induced by 300 and 392 MeV Protons

Tadahiro Kin[1], Fuminobu Saiho[1], Sin-ya Hohara[1], Katsuhiko Ikeda[1], Kiyohisa Ichikawa[1], Yuichiro Yamashita[1], Minoru Imamura[1], Genichiro Wakabayashi[1], Nobuo Ikeda[1], Yusuke Uozumi[1], Masaru Matoba[1], Norihiko Koori[2]

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Multistep direct processes in proton production reactions were investigated with proton beam of 300 and 392 MeV bombarding targets nuclei: $^{159}$Tb, $^{181}$Ta, $^{197}$Au, and so on. Energy spectra were measured at several laboratory angles from 20° to 105° and compared with two theoretical models, the quantum molecular dynamics and the intranuclear cascade model. At intermediate energy, the double differential cross section is sensitive to ground state in codes. Then we found that a more realistic ground state led better accounting of measured data.

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## [319] Motivation for New Measurements of the Am Isotopes.

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Starting from the observation that the $^{241}$Am neutron data were not re-evaluated for jeff3.0 and that three new measurements have been performed since the official release of jef2.2 in 1990, a synthesis on the $^{241,242,243}$Am isotopes neutron data has been performed. Various comparisons have been done with recent evaluated data files (JENDL3.3, ENDF-BVI.8, BROND3 and JEFF3.0). Large discrepancies between differential measurements and 'integral' data relative to americium have motivated a review of the available experimental data and evaluated files. This work points to strong discrepancies on branching ratio values between the various evaluations and their actual treatment in current reactor

calculations. In addition, the need for new measurements to reach the desired target accuracy on Am isotopes neutron data is emphasized and a list of appropriate new measurements is provided. This paper shows that considerable work is needed to produce well-motivated measurement specifications starting from the users' needs.

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## [335] Evaluation of n + W cross-section data up to 150 MeV neutron energy

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Tungsten is a high priority material for various fusion technology applications. It is the primary candidate for the armour of plasma facing components and is a major constituent of the reduced activation ferritic-martensitic steel Eurofer considered as structural material of future fusion power reactors. In the European Fusion Technology Programme, highest priority has been assigned to high quality data evaluations for the tungsten isotopes. This includes the neutron energy range above 20 MeV to enable intermediate energy calculations of the IFMIF (International Fusion Irradiation Materials Irradiation Facility) neutron source facility which will be used for high fluence irradiations of the Eurofer steel. A corresponding task on the evaluation of neutron cross-sections for the W isotopes has been launched as part of the European Fusion File (EFF) project.

This paper presents results of the evaluations for the n + W reactions up to 150 MeV. The GNASH code was used for the calculation of nuclear reaction cross sections and the ECIS code for the neutron elastic and direct inelastic scattering cross sections. Recent high energy experimental data were taking into account for evaluating the total and nonelastic cross sections. A set of optical model potentials up to 150 MeV was chosen on the bases of detailed comparisons of available experimental data and calculations with ECIS and the SCAT2 code. Both global and local potentials for neutrons, protons, deuterons, tritons and alphas were considered. To improve the neutron emission spectra, collective excitations were also included in GNASH. The Ignatyuk nuclear level densities were used for statistical model calculations. Double-differential cross sections of the emitted particles were calculated on the basis of the Kalbach systematics.

As a general rule, the ENDF/B-VI.8 data were adopted below 20 MeV with some corrections applied to achieve agreement with recent experimental data. Thus complete ENDF data files were prepared for the W isotopes covering the full energy range data up to 150 MeV. The double differential reaction cross sections were represented in the MF=6, MT=5 data format.

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# Poster A

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## [15] The Investigation of Neutron Cross-sections Structure of Nb, Mo, Rh, Ho and W in the resonance region.

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The results of gamma-ray multiplicity spectra and transmission measurements for $^{93}$Nb, Mo, Rh, W, Ho and $^{238}$U in energy range 21.5eV – 46.5 keV are presented. Gamma spectra from 1 to 7 multiplicity were measured on the 501m and 121m flight paths of the IBR-30 using a 16-section scintillation detector with a NaI (Tl) crystals of a total volume of 36 l and a 16-section liquid scintillation detector of a total volume of 80 l for metallic samples of 50, 80mm in diameter and 0.1, 1.5mm thickness. Besides, the total cross-sections of Nb, Mo, Rh, W were measured by means batteres of B-10 and He-3 counters on the 124m , 504m and 1006m flight paths of the IBR-30. Spectra of multiplicity distribution were obtained for resolved resonances in the energy region E=30-6000 eV and for energy groups in the energy region E=21.5eV – 46.5keV. Standard capture cross-sections of $^{238}$U and experimental gamma-ray multiplicity spectra of $^{93}$Nb, Mo, Rh, W and $^{238}$U were used for determination of capture cross-sections in energy groups. Similar values were calculated using the ENDF/B-6 and JENDL-3 evaluated data libraries with the help of the GRUCON computer program.

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## [16] The Investigation of the Doppler-Effect of the a- Value of $^{235}$U and $^{239}$Pu for Different Temperatures.

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The time-of-flight spectra for $\gamma$-ray multiplicities from 1 to 15 were measured on the 121 m flight path of IBR-30 pulsed neutron booster using the 16-section liquid scintillation detector for a thin metallic $^{235}$U radiator-sample (0.25 mm) and $^{239}$Pu (0.3 mm) at the presence of the $^{235}$U and $^{239}$Pu filter-samples with a thickness of 0.5 mm at two temperatures (100 K and 293 K). Multiplicity spectra, Doppler-coefficients of the capture, fission cross-sections and of the alpha values were determined from the time-of-flight spectra for above-mentioned temperatures.

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## [24] Measurements of neutron-induced fission cross sections of $^{205}$Tl, $^{204,206,207,208}$Pb and $^{209}$Bi using quasi-monoenergetic neutrons of 35 MeV to 174 MeV.

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Nuclear data on intermediate energy nucleon-induced reactions are needed for the development of theory of nuclear interaction and nuclear structure. They also are necessary for the development of new concepts of nuclear energy production and transmutation of nuclear waste with the use of accelerators. Lead and lead-bismuth eutectics are regarded as prospective materials for spallation-based neutron production targets. For this reason, the neutron-induced fission cross section of $^{208}$Pb in the energy range up

to 200 MeV was included in the High Priority Request List for necessary measurements for accelerator driven system research [1]. In addition, fission cross section of $^{209}$Bi is relevant as a secondary standard for neutron fluence measurements at intermediate energies.

Moreover, nucleon-induced fission cross sections for the spherical doubly magic nucleus $^{208}$Pb and neighboring nuclei are of interest for development of accurate models of the fission process, because of possible manifestations of nuclear shell effects.

The cross sections for neutron-induced fission of $^{205}$Tl, $^{204,206,207,208}$Pb and $^{209}$Bi were measured in the energy range from 35 MeV to 174 MeV using a multi-section Frisch-gridded ionization chamber. Such a detector has the advantage over ordinary parallel-plane ionization chambers that the discrimination of fission events against the background caused by light particles is better [2]. The neutron-induced fission cross section of $^{238}$U was employed as a reference [3].

The measurements were performed at the neutron beam facility of the The Svedberg Laboratory in Uppsala, Sweden. A quasi-monoenergetic neutron beam with peak energies from 35 MeV to 174 MeV was produced using the $^{7}$Li(p,n) reaction. The time-of-flight method was employed to discriminate fission events caused by "peak" neutrons from those induced by low-energy "tail" neutrons.

The neutron-induced fission cross section of natural lead, which is of great practical importance, has been obtained by summing the cross sections for the separate lead isotopes, weighted by the natural abundancies.

The data obtained are compared with the existing experimental data on neutron-induced fission cross sections of $^{nat}$Pb and $^{209}$Bi.

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2. V.P. Eismont, A.V. Kireev, I.V. Ryzhov, S.M. Soloviev, G.A. Tutin, H. Conde, K. Elmgren, N. Olsson and P.-U. Renberg. Proc. 3rd Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications, Praha, Czech Republic, June 7-11, 1999, http://www.fjfi.cvut.cz/con_adtt99/a_confer/a_info/list_pap.htm, Mo-O-C7.
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## [46] Production of light charged and neutral particles in the proton and alpha induced reactions on $^{nat}$ Si target between 20 and 65 MeV

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Destructive and upsetting effects of impinging nuclear radiation (from radioactive sources or particle beams) and cosmic-rays on natural silicon, principal constituent of semi-conductor detectors or electronic devices incorporated in the microelectronic of space and avionic systems, are presently of current interest for industrial and safety applications.

Then it became urgent to build a large and accurate data base for neutral and charged particles basic and microscopic interactions in $^{nat}$ Si through in-beam experiments in order to obtain a realistic interaction scheme to improve the existing models and their capabilities to reproduce and understand the observed phenomenon in electronic subsystems such as "single event upset".

Therefore we undertook such studies at the Louvain-la-Neuve cyclotron facility using proton and alpha beams of energies ranging between 20 and 65 MeV in order to provide inclusive data such as: $\frac{d^2\sigma}{d\Omega dE}$, $\frac{d\sigma}{dE}$, $\frac{d\sigma}{d\Omega}$ and $\sigma_{tot}$ cross-sections of all possible secondary neutral and light charged (LCP) emitted particles (n, p, d, t, $^3He$, $^4He$, Li and Be).

Detection of the LCP was achieved by using a set of several Si triple-telescopes and Si-Si-CsI telescope assemblies. Neutron detection was insured by the 96 DEMON large volume liquid scintillation counters surrounding the reaction chamber at two meters distance-of-flight from the target. This experimental set-up has allowed i) an excellent identification of the different light and neutral particle species (in Z and A) and ii) the measurements of their energies and angular distributions.

We will report on the presently available results and their interpretation with a confrontation to predictive model codes such as GNASH and ICM [1,2].

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## [53] Systematic measurement of keV-neutron capture cross sections and capture gamma-ray spectra of Zr isotopes

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The neutron capture cross sections of Long-Lived Fission Products (LLFPs: Se-79, Zr-93, Tc-99, Pd-107, Sn-126, I-129, Cs-135) are indispensable for the study on the nuclear transmutation of LLFPs. As for Zr-93, however, there is only one data set in the keV region[1], so we plan to measure its capture cross sections in the keV region. The preparation of Zr-93 sample is now in progress, and the sample will contain much isotopic impurity. Therefore, the capture cross sections and capture gamma-ray spectra of all stable Zr isotopes are necessary for the data analysis of Zr-93 experiment in order to derive the capture cross sections of Zr-93. From this viewpoint, we started the systematic measurement of keV-neutron capture cross sections and capture gamma-ray spectra of Zr isotopes.

A Time of Flight (TOF) method was adopted with pulsed keV neutrons from the $^{7}$Li(p,n)$^{7}$Be reaction by a 1.5-ns bunched proton beam from the 3-MV Pelletron accelerator of the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology. About 1 g of enriched oxide sample ($ZrO_2$) was prepared for each of Zr-90,91,92,94 and was contained in a graphite case with an inner diameter of 20mm. A gold (Au) sample was used as a standard. The capture gamma rays from the Zr or Au sample were detected with an anti-Compton NaI(Tl) spectrometer. The signals from the spectrometer were recorded in PC as two-dimensional data of Pulse Height (PH) and TOF. A PH weighting technique and the standard capture cross sections of Au-197 in ENDF/B-VI were employed to derive the capture cross sections of Zr isotopes. Finally, the capture gamma-ray spectra were derived by unfolding the corresponding PH spectra.

[1] R. L. Macklin, Astrophys. Space Sci., 115, 71 (1985)
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## [56] Hafnium Resonance Parameter Analysis Using Neutron Capture and Transmission Experiments

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The focus of this work is to determine resonance parameters for stable hafnium isotopes in the 0.005 - 200 eV region, with special emphasis on the overlapping Hf-176 and Hf-178 resonances near 8 eV. The large neutron cross section of hafnium, combined with its corrosion resistance and excellent mechanical properties, make it an ideal material for controlling nuclear reactions.

Experiments measuring neutron capture and transmission were performed at the Rensselaer Polytechnic Institute (RPI) LINAC using the time of flight method. Li-6 glass scintillation detectors were used for transmission experiments at flight path lengths of 15 and 25 m. Capture experiments were done using a sixteen section NaI multiplicity detector at a flight path length of 25 m. These experiments utilized various thicknesses of metallic and isotope-enriched liquid samples. The liquid samples were designed to provide information on the Hf-176 and Hf-178 contributions to the 8 e V doublet without saturation.

Data analysis was done using the R-matrix Bayesian code SAMMY version M6 beta. SAMMY is able to account for experimental resolution effects for each of the experimental setups at the RPI LINAC, and also can correct for multiple scattering effects in yield data. The combined capture and transmission data analysis yielded resonance parameters for all hafnium isotopes from 0.005 - 200 eV. Resonance integrals were calculated along with errors for each hafnium isotope using the NJOY and INTER codes. The isotopic resonance integrals calculated were significantly different than previous values; however the calculated elemental hafnium resonance integral changed very little.

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## [62] Investigations on the neutron induced reaction cross sections in the 8-12 MeV problem range

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A fast pneumatic rabbit system developed at the MGC-20 variable energy cyclotron of ATOMKI rendered the measurements of cross section curves for neutron induced reactions in the 7-12 MeV range even for short-lived residual nuclei possible. Special attention was paid for the following reactions: $^{19}$F(n,p)$^{19}$O, $^{26}$Mg(n,$\alpha$)$^{23}$Ne, $^{31}$P(n,$\alpha$)$^{28}$Al, $^{50}$Ti(n,p)$^{50}$Sc, $^{54}$Cr(n,p)$^{54}$V, $^{62}$Ni(n,p)$^{62}$Co, and $^{208}$Pb(n,p)$^{208}$Tl. In addition, systematic study was carried out on the excitation functions of (n,2n), (n,n'$\gamma$) and (n,p) reactions for different Pb isotopes. Standard data for the normalizations of these excitation functions were also measured at around 14 MeV neutron energy using the D-T generator of the IEP. For the determination of the cross sections the activation method was applied using high energy resolution gamma spectrometers, gas flow and end-window beta-counters. These investigations were undertaken with the aim to obtain new and precise data needed in various fields of science and technology e.g. for the improvement of neutron data libraries, nuclear model calculations, the CTR program, ADE systems, neutron methods for non-intrusive inspections.

This work was supported in part by the Hungarian Research Fund (OTKA T037190, D35480), the International Atomic Energy Agency, Vienna (Contract No. 10886/R2) and the EURATOM, Geel (Contract No. IRMM/ST/2001-248"14-CCR 478519).

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## [64] Complete and Incomplete Fusion in the Reaction of $^{16}$O with $^{74}$Ge

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There has been a considerable interest in the study of complete fusion (CF) and incomplete fusion (ICF) in the heavy ion induced reaction at the projectile energy range between 5-10 MeV/nucleon. The mechanism of ICF reactions is still not clearly understood particularly with regards to the angular momentum involved in the process. ICF particularly be considered as a process in which the projectile breaks up into two fragments, near the surface of a target nucleus, one of which escapes with relatively unchanged velocity while the other fuses with the target to form an excited composite system, which subsequently de-excites in the usual way, by particle evaporation. In the process of ICF, linear momentum of the entrance channel is not transformed completely to the composite system. In the present work, excitation functions of the evaporation residues produced in $^{16}$O induced reactions on enriched $^{74}$Ge isotope (enrichment 98.9%) have been measured by activation technique, at twelve energies between 60.2 and 111.6 MeV. Targets of various thickness between 80-270 $\mu$g/cm$^2$ were made by vacuum evaporation technique an aluminum backing of 1.14 mg/cm$^2$ . The experiment has been performed at VECC Heavy Ion Accelerator Facility, Kolkata (India). The irradiation was performed by keeping the target assembly normal to the beam facing the sample $^{74}$Ge. The aluminum backing serves the purpose of catcher foil to trap the recoiling nucleus as well as energy degrader. $\gamma$-activities were recorded by a 100cm$^3$ HPGe detector, coupled to PC based data acquisition system at VECC.

Some of the measured excitation functions which have been reported here are: $^{74}$Ge($^{16}$O, 4n)$^{86}$Zr, $^{74}$Ge($^{16}$O, p4n)$^{85}$Y, $^{74}$Ge($^{16}$O, 2$\alpha$3n)$^{79}$Kr, $^{74}$Ge($^{16}$O, $\alpha$3n)$^{83}$Sr and $^{74}$Ge($^{16}$O, $\alpha$p2n)$^{83}$Rb. In order to see the contribution of CF the measured EFs have been analyzed with the theoretical predictions of code ALICE-91. This code does not take into account ICF process and hence deviation of the measured EFs from theoretical calculations may be attributed to the presence of ICF process. The reactions $^{74}$Ge($^{16}$O, 4n)$^{86}$Zr, $^{74}$Ge($^{16}$O, p4n)$^{85}$Y and $^{74}$Ge($^{16}$O,2$\alpha$3n)$^{79}$Kr seem to take place through CF process, while the reactions $^{74}$Ge($^{16}$O, $\alpha$3n)$^{83}$Sr and $^{74}$Ge($^{16}$O,$\alpha$p2n)$^{83}$Rb show the presence of ICF process along with CF process, especially at higher projectile energies.

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## [69] Near Coulomb Barrier Heavy Ion Induced Fission Reactions

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Heavy Ion induced fission reactions at Coulomb barrier energies have provided a wealth of information regarding fission dynamics, role of entrance channel, nuclear structure of the interacting species and the compound nuclei. Systematic measurements of fission cross sections have been carried out for a range of projectiles from $^{9}$Be to $^{19}$F interacting with Th and U targets. The presence of pre - equilibrium fission ( non - compound fission) in addition to compound nuclear fission has been established from these studies. The importance of nuclear shell effect in influencing the decay of the compound nuclei has also been brought out from these investigations. A review of the heavy ion fission studies performed by BARC group in the last 10 years covering the above aspects will be presented.

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## [93] Experimental Study of Energy Dependence of Proton Induced Fission Cross Sections for Heavy Nuclei in the Energy Range 200-1000 MeV

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The results of the total fission cross section measurements for $^{nat}$Pb, $^{209}$Bi, $^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, $^{237}$Np and $^{239}$Pu nuclei at the proton energy range 200-1000 MeV with step 100 MeV are presented. Experiments were carried out at 1 GeV synchrocyclotron of PNPI with the updated beam system that allowed one to have proton beams in all energy range with intensities up to $10^7$ protons/s. The measurement method is based on the registration in coincidence of both complementary fission fragments by two gas parallel plate avalanche counters, located at a short distance and opposite sides of investigated target. The insensitivity of parallel plate avalanche counter to photons, neutrons and protons allowed us to place the counters together with target between immediately in the proton beam thereby providing a large solid angle acceptance for fission fragment registration. The proton flux on the target to be studied was determined by direct counting of protons by scintillation telescope and using secondary reaction of elastic proton scattering by $CH_2$ target. Obtained results are compared with other experimental data and show that the fission cross sections do not depend strongly on the incident proton energy over this entire energy range.

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## [99] Neutron Capture and Transmission Measurements on $^{103}$Rh down to Thermal Energies

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Improved capture cross sections for various stable fission products, with a high capture probability are on the NEA High Priority Nuclear Data Request List. Improved data for stable fission products are motivated by the objective to optimise the use of nuclear power plants. The requests concentrate mainly on the thermal energy and the energy region covering the first strong resonance(s). Improved capture data for certain lanthanides, in both the thermal and fast region, are also required for fuel cycles using reprocessed fuel. To improve the above-mentioned data we initiated a collaboration with the CEA Saclay (F) and started the measurements for the poisoning nucleus $^{103}$Rh. To access the cross section in the thermal energy region, the capture experiments were performed at a 15m-flight path and with the LINAC operating at 40Hz. A boron ionisation chamber was used to measure the neutron flux. Two Bicron $C_6D_6$ detectors were used to determine the capture yield. The background was determined using Cd, Rh, Au, W, Co, Bi and Na filters. The neutron energy scale for the capture measurements in the meV-region is

verified by means of the prominent Bragg-reflection cuts in Be at 5.24 and 6.84 meV. The transmission experiments were carried out for energies above 0.14 eV, at a 50m flight path with GELINA operating at 100 Hz. The neutron detector consisted of a 0.25" thick NE912 Li-glass viewed by a 5" EMI KQB 9823 photomultiplier placed outside the neutron beam. A Cd anti-overlap filter was used for this experiment. The background was monitored by the Cd anti-overlap filter and by the black resonance filters of Au, Co, and Na, kept permanently in the beam. The results of both experiments were analysed using the resonance shape analysis codes REFIT and SAMMY. The thermal capture cross section, resulting from a combined analysis of capture and transmission data, is 140 ± 2 b compared to the 145 b reported in the evaluated data files in ENDF/ B-VI. This cross section is in good agreement with results from integral measurements.

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## [122] Experimental determination of cross section of d-induced reactions on $^{nat}$Pd

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In our ongoing effort of systematic investigation of cross sections of nuclear reactions induced by light charged particles we recently studied the production of Ag radionuclides from natPd targets. We present here the experimental results for the deuteron induced reactions between thresholds and 21MeV for the short lived ($T_{1/2}$ <4h) radionuclides $^{103,104,112}$Ag.and for the longer lived $^{105,106m,110m,111}$Ag. Two stacks containing high purity natPd foils (thickness 7.99 micron) were irradiated at the VUB cyclotron with 20.5 and 15.1 MeV deuteron beams. The number of foils assured covering of the whole energy range down to the threshold of the (d,xn) reactions and resulted in energy overlap between the 2 stacks. Interleaved high purity Ti foils served as monitors to obtain reliable characteristics (energy and intensity) for the deuteron beam by comparison of the cross sections of the $^{nat}$Ti(d,x)$^{48}$V reaction with reference values over the whole energy range studied. These foils also allowed to check the energy degradation in the stacks. Direct $\gamma$-spectrometry starting from a 1 hour after EOB up to after several weeks resulted in the identification and quantification of the activity induced for the different radionuclides studied. Excitation curves and production capabilities for the medically relevant $^{104m,g}$Ag (PET imaging) and $^{111}$Ag (therapeutic applications) are presented and the contamination with $^{110m}$Ag is discussed. The excitation function for the $^{104}$Pd(d,3n)$^{103}$Ag reaction (leading to a precursor of therapeutic $^{103}$Pd) allows to conclude that this pathway is not an alternative production route for $^{103}$Pd. Also for the reactions leading to the longer lived $^{105,106m}$Ag , useful in Thin Layer Activation and as markers, the cross sections and the thick target yields are presented. As detailed excitation functions for nearly all these reactions are measured here for the first time only limited comparison with literature values (thick target yields obtained by Dmitriev et al [1]) is reported. For all reaction products the contribution of the different (d,xn) channels on the individual stable Pd isotopes present in natPd are calculated by the ALICE-IPPE code.

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## [123] Experimental study of the cross sections of reactions induced by alpha-particles on $^{209}$Bi.

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Although the possible therapeutic use of the alpha-emitting radionuclide $^{211}$At is put forward since many years, it is only recently that attention regained and that confirmation of earlier obtained information on production possibilities is asked for. In order to check the cross sections of the $^{209}$Bi$(\alpha, 2n)^{211}$At reaction and of reactions leading to possible contaminants, two stacks of foils were irradiated at the VUB-Cyclotron with a-beams of 38.5 and 40.5MeV incident energy. The target foils consisted of rather

thick (1 to 4 mg/cm$^2$) metallic Bi evaporated onto pure Cu (10.83micron) or Al (23.92micron) backings. The backings served as recoil catchers and as monitor foils for exact determination of beam parameters and allow an internal consistency check of the energy degradation along the stack. The activities of $^{211}$At, $^{211}$Po and $^{210}$Po were assessed through direct alpha-spectrometry taking advantage of the independent alpha-lines and using a Si-surface barrier detector at different times after EOB. The important energy degradation in the targets of the emitted alpha-rays resulted in broadened peaks often showing the effects of thermal diffusion towards the surface of the targets of the radionuclides formed in the Bi-bulk. The efficiency calibration of the set-up was performed for different sample-detector distances using a $^{228}$Th source. The activity of $^{210}$At was measured by direct gamma-spectrometry shortly after EOB. The measured cross sections for $^{211}$At, $^{210}$At, $^{211}$Po and $^{210}$Po are in good agreement with the earlier published results of Ramler et al. [1] and of Lambrecht and Mirzadeh [2]. The small contribution of the $^{209}$Bi$(\alpha,t)^{210}$Po reaction to the direct production of $^{210}$Po, apart from the decay of parent $^{210}$At, could be confirmed. Theoretical thick target yields and optimised irradiation parameters (incident energy and target thickness), in function of acceptable $^{210}$At–$^{210}$Po contamination levels and time of use, will be presented.

[1] W.J. Ramler, J. Wing, D.J. Henderson and J.R. Huizenga, Physical Review, 114, 1958, p 154.
[2] R.M. Lambrecht and S. Mirzadeh, Int. J. Applied Radiation and Isotopes, 36, 1985, p 443.

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## [124] Experimental determination of cross section of alpha-induced reactions on $^{nat}$Pd

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In our systematic investigation of possible production routes of medically and technically interesting Ag radionuclides we included the study of alpha induced reactions on $^{nat}$Pd targets. A stack containing 14 high purity $^{nat}$Pd foils (thickness 7.99 micron) was irradiated at the VUB cyclotron with a 36.5MeV alpha-particle beam. Interleaved high purity Cu foils (7.61micron thick) served as monitor foils to obtain reliable beam characteristics (energy and intensity) by comparison of the cross sections of the $^{nat}$Cu$(\alpha,x)^{67}$Ga and $^{nat}$Cu$(\alpha,x)^{65}$Zn reactions with reference values over the whole energy range studied. These foils also allowed to check the energy degradation in the stack. Direct gamma-spectrometry at different times after EOB resulted in the identification and quantification of the activity induced for the short lived ($T_{1/2} <$ 4h) radionuclides $^{103,104,112}$Ag and $^{105,111m}$Cd.and for the longer lived $^{105,106m,110m,111}$Ag. The excitation functions for the reactions leading to the above mentioned production reactions will be presented for the first time. For some selected reaction products a comparison between the p,d, and alpha induced pathways and a discussion of the respective merit of the production routes (yield and contaminants) will be made. Analysis of the contributing reactions on the different stable isotopes of Pd will be based on model calculations performed with the ALICE-IPPE code.

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## [130] Mass, isotopic yields and kinetic energy measurements for $^{245}$Cm($n_{th}$,f)

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The mass, charge yields and the kinetic energy distribution for the fission fragments from the thermal-neutron induced fission of $^{245}$Cm were measured at the Lohengrin mass spectrometer at the Institut Laue Langevin, France. Using an ionization chamber coupled to the mass separator, we have measured data for the super-asymmetric mass region (from $A = 67$ to $A = 77$). These results of mass and isotopic yields are compared with those of other compound nuclei to highlight the shell effect at mass 70 for the $^{246}$Cm$^*$ compound-nucleus system. Furthermore, the proton odd-even effect is presented for the super-asymmetric fission and compared with previous results for $A > 80$. Mass yields and kinetic energy distributions for the heavy mass region (from $A = 130$ to $A = 167$), measured with the same method, are also presented. These experimental data are compared with the evaluations from the libraries JEF2.2 and ENDF/B-VI and with the A. Wahl's $Z_p$ model. This considerably extends the data set previously known for the light and heavy mass peaks.

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## [146] Search for scission neutrons in the thermal fission of U-235 and Pu-239.

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The number and energies of the neutron emitted in the in the thermal neutron induced fission of Pu-239 and U-235 have been measured as a function of the fragment energy and the angle between fragment direction and direction of the neutron emission. A cylindrical double gridded ionization chamber has been used for fixation of the fission event and measurements of emission angles of fission fragments with respect to the target plane. Neutron energy has been measured using time-of-flight method with 12 neutron detectors spherically surrounded the fission chamber. A neutron angular distribution has been measured relative to Cf-252 in two ways - using fixation of the fragment emission angle close to the normal to the fissile target plane and neutron registration by full set of detectors and the second one - using of two neutron detectors located along the axis of the fission chamber and registration of the all emission angles of fragments with respect to the normal of the target. Such an analysis of the experimental data has to provide a reduction of the systematical uncertainties in order to search the deviation in the neutron angular distribution obtained from those specific for the assumption that all neutrons are emitted from fully accelerated fragments. Being found such a deviation could mean a presence of the scission neutrons. The knowledge about the scission neutron is very important for better understanding of fission dynamics, as well as for more reliable evaluation of the fission prompt neutron spectra.

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## [148] TOTAL CROSS SECTION AND SELF-SHIELDING EFFECTS OF THE CR-52 ISOTOPE MEASURED AT KYIV RESEARCH REACTOR NEUTRON FILTERED BEAMS

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Self-shielded values of total neutron cross section of a set of Cr-52 samples were measured with 24 and 58 keV neutron filtered beams at Kyiv Research Reactor. These investigations were done to obtain the real unshielded values of Cr-52 cross section for neutron energies 24 and 58 keV, as the Evaluated Nuclear Data Libraries (ENDF) give the dispersion of cross section for these energies 60 and 40%, correspondingly. Meanwhile, the needs of reactor technology urge on the accuracy of this value better than 3% in the energy range 10 eV-20 MeV.

For 24 keV filter we used here the composition consisted of Fe, Al, S, B-10 to receive the quasi-monoenergy beam with the average energy 24.34 keV and for 58 keV filter we used correspondingly Ni-58, S, V, B-10, Al, Pb to receive the beam with energy 58.8 keV. Beam line purity was about 99% and 94%, correspondingly.

High intensity of neutron beams made it possible the measurements with accuracy better than 1%, and as the result, we received the set of measured cross sections for 12 samples with thickness in the range (0.0137-0.400) at/barn. The linear extrapolation to zero thickness gives the values $2.218 \pm 0.064$ barn (2.9% accuracy) for average energy 24 keV and $7.31 \pm 0.14$ (1.9%) for 58 keV. Now we consider these results as preliminary and continue their processing.

ENDF libraries give the total cross section values, averaged on filter widths for 24 keV filter in the range 1.19 - 2.82 barn and for 58 keV one in the range 4.50 - 7.03 barn.

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## [180] Measurement of neutron inelastic scattering cross sections for $^{209}$Bi from threshold up to 18 MeV

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The investigation of inelastic scattering of neutrons on structure materials used for the design of the new generation of reactors was continued at Gelina facility with $^{209}$Bi. The interest for $^{209}$Bi, the only one stable isotope of bismuth, is motivated for instance by its possible use in the spallation module and the moderator/coolant of an accelerator driven system (ADS). Inelastic scattering contributes with about 30% to the total neutron cross-section of $^{209}$Bi. It was recently demonstrated that uncertainties of the lead and bismuth inelastic scattering cross sections produce a 2% uncertainty in $k_{eff}$ for an ADS. This motivates a detailed study to obtain better precision data for inelastic scattering. Here new data are presented for continuous energy gamma-ray production cross sections up to about 18 MeV. From these total and level inelastic cross sections are deduced. The new continuous energy and high resolution data completely fix the inelastic scattering cross sections in the first few MeV above the threshold, which is of particular importance to applications. The data at higher energy are valuable for benchmarking of model calculations.

The white neutron beam, produced by bombarding a rotary uranium target with electrons of a nominal energy of 105 MeV and an average current of $70\mu A$, is scattered inelastically by a metallic sample of $^{209}$Bi. The $\gamma$-rays from the reaction $^{209}$Bi$(n, n'\gamma)^{209}$Bi are detected with two large volume HPGe detectors placed at $110^o$ and $150^o$ with respect to the beam direction. These angles are the roots of the fourth order Legendre polynomial which allows to make the correction for angular distribution, the error being negligible, in the contribution of the $8^{th}$ order Legendre polynomial.

The absolute efficiency of the HPGe detectors has been measured with standard point-like calibration sources and, by means of MCNP simulations, the correction for the gamma ray self-attenuation in the real $^{209}$Bi target as well as for the effect of extended volume source has been determined.

The neutron flux has been measured with a multilayer $^{235}$U fission chamber. The measurements were done at the 200 m time-of-flight path at 800 Hz repetition rate of the neutron burst. For the main transitions the inelastic cross-section is given with an incident neutron energy resolution ranging from 1.1 KeV at 1 MeV to 35.7 KeV at 10 MeV, the overall statistical error being less than 5%. Gamma rays which decay from levels up to about 3.1 MeV excitation energy were observed. Based on the known level scheme of $^{209}$Bi lower limits for level and total inelastic cross-sections are constructed. The results will be compared with existing experimental data. Earlier, results have been obtained for $^{52}$Cr and $^{58}$Ni with the same setup and methodology.

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## [196] Measurement of evaporation residue cross sections for sub-barrier $^{16}$O+$^{238}$U reaction

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Fission fragment angular distributions for heavy-ion reactions using actinide target show anomalously large anisotropy (A=W(180°)/W(90°)) compared to the transition state model. By assuming the quasi-fission being responsible for the large anisotropy, it was concluded [1] in the $^{16}$O+$^{238}$U reaction that quasi-fission is dominated and complete fusion is hindered in the sub-barrier energy region, where the interaction of the projectile is restricted to the tip of the prolately deformed target. In order to verify the discussion, we measured the evaporation residue (ER) cross sections for $^{16}$O + $^{238}$U as the direct evidence of complete fusion. The data was taken from $E_{c.m.}$= 100 MeV down to 72 MeV corresponding to 0.88 times the average Coulomb barrier (81.4 MeV).

The $^{16}$O beams were supplied by the JAERI-tandem accelerator and bombarded the natural $^{238}$U target. The ERs recoiling out of the target were transported by a He-gas loaded with KCl aerosol

clusters through a capillary and deposited at a periphery of a 80-cm-diameter wheel. The wheel was rotated every 150 s to collect a new deposit and to detect $\alpha$ decays by a series of 18 silicon detectors in order to determine the production rate.

The $\alpha$ decays of $^{250,249,248}$Fm were clearly observed and the corresponding cross sections were determined. The cross sections were compared to a statistical model calculation. In the calculation, the fusion cross section was determined by a coupled channel code [2], which takes into account the static deformation of the target and reproduces the experimental fission cross sections for $^{16}$O + $^{238}$U. At and above the Coulom barrier, the calculation nicely reproduced the experimental data. Also in the sub-barrier region, the experimental data agrees with the calculation and the fusion hindrance was not observed. We obtained a conclusion that complete fusion occurs in the sub-barrier region and the quasi-fission is not the reason for the anomalously large fission anisotropy.

References

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[2] K. Hagino et al., Computer Phys. Communication. 123, 143 (1999).

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## [198] Light Charged-Particle Production Activation Cross Sections of Zr isotopes from 14 to 20 MeV

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Neutron-induced reaction cross sections for structural materials are basic data for evaluation of the processes in these materials under irradiation in reactors. Neutron-induced reactions on zirconium are of particular importance in a wide range of applications [1]. In addition to its use in current reactors Zr is present in most innovative concepts. Of particular importance to structural materials are the hydrogen and helium production cross sections that impact material damage and handling limits. Radiation hazards and decay heat are associated with the activation products. Studies of exitation functions of fast neutron-induced reactions are important for testing nuclear models. In the investigated energy region many reaction channels are open (e.g., elestic and inelastic scatering, radioactive capture, (n,2n), (n,p), (n,$\alpha$), (n,np), (n,nd), (n,n$\alpha$) etc.). To account for the reaction channels that are open the direct, preequilibrium and statistical processes should be considered.

New results were obtained for the $^{90}$Zr(n,$\alpha$)$^{87m}$Sr, $^{90}$Zr(n,p)$^{90m}$Y $^{90}$Zr(n,2n)$^{89m}$Zr, $^{91}$Zr(n,x)$^{90m}$Y, $^{91}$Zr(n,p)$^{91m}$Y, $^{92}$Zr(n,x)$^{91m}$Y, $^{92}$Zr(n,p)$^{92}$Y, and $^{94}$Zr(n,p)$^{94}$Y activation reaction cross sections in the energy range from 14 to 21 MeV. The irradiations were carried out at the 7MV Van de Graaff accelerator at IRMM, Geel. Quasi-mono-energetic neutrons with energies between 14.8 and 20.6 MeV were produced via $^{3}$H(d,n)$^{4}$He reaction at 1, 2, 3, and 4 MeV incident deuteron energy. Both natural and samples enriched in $^{90}$Zr, $^{91}$Zr and $^{92}$Zr were used. All reaction cross sections measured in the present work are referenced to $^{27}$Al(n,alpha)$^{24}$Na standard reaction cross section. Neutron flux spectra were determined using neutron-spectrum information obtained by time-of-flight method and spectral index method that involves various monitor reactions with distinct energy thresholds. Standard gamma-ray spectrometry was employed for measurement of radioactivity. Corrections have been applied for sample irradiation and counting geometry, beam intensity variation during irradiation, background neutrons, neutron absorption and scattering, gamma-ray absorption and gamma-ray sum coincidences, and correction for interfering reactions leading to the same product. For more details about the method see Ref. 2 and Ref. 3.

The measurment results are compared with work by other authors, current evaluated data files and new model calculations.

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3) P. Reimer et al., Phys. Rev. C65, 014604 (2001)

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## [204] Neutron Emission Spectra from Inelastic Scattering on Ni, Mo and Pb with a White Neutron Source at FIGARO

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Inelastic neutron scattering has been used in studies of nuclear structure and reaction mechanisms for many years. The data over a wide range of energies are also of great importance for applications. Experimentally, inelastic scattering has been studied with monoenergetic or continuous-in-energy (white) neutron sources. With the former, neutron-emission spectra can be measured by time-of-flight techniques for incident neutron energies available with monoenergetic sources ($E_n < 8$ MeV and 13 MeV $< E_n <$ 17 MeV). Gamma-ray production can be studied with either type of source. In this work, we measure neutron-emission spectra with incident neutrons produced by a white source by use of a double time-of-flight technique. This approach is intended to extend the neutron energy range available with monoenergetic sources and to take advantage of white-source techniques to measure these quantities over a wide range of incident neutron energies simultaneously in one experiment. To signal an inelastic scattering event, the gamma ray from the first excited level of the target nucleus to the ground state is detected either by a high-resolution germanium detector or a barium-fluoride scintillator. This is the start signal on measuring the time of flight of the emitted neutrons to liquid scintillators about 1 meter from the sample. From the time-of-flight information, the energy of the emitted neutrons can be calculated. We have studied the energy spectra of outgoing neutrons from the reactions Ni(n,n-$\gamma$)Ni, Mo(n,n-$\gamma$)Mo and Pb(n,n-$\gamma$)Pb as a function of incident neutron energy, using the white neutron beam of the WNR facility at the Los Alamos Neutron Science Center and the FIGARO facility over a range of incident neutron energies from threshold to 20 MeV. The high-resolution gamma-ray detector signals inelastic events on specific isotopes so that isotopic information can be obtained with elemental samples. Results of the emission spectra will be presented and compared with predictions of nuclear model calculations.

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## [218] Cross-section measurements of the $^{29}$Si$(p, 2\alpha)^{22}$Na reaction by residual activity

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A stacked-foil method was used to obtain the excitation function of the $^{29}$Si$(p, 2\alpha)^{22}$Na ($Q = -14273.7(5)$ keV) reaction for energies near the threshold. Measurements by residual activity were performed in eight silicon foils irradiated with a 24 MeV proton beam. A careful study about the existence of some impurities of $^{23}$Na in the silicon sample (which could affect the results due to the fact that the magnitude of the $^{23}$Na neutron capture cross section is much larger than the $^{29}$Si$(p, 2\alpha)^{22}$Na cross section) was made using (n$_{thermal}$,$\gamma$) reaction with a thermal neutron beam with a flux of $10^{13}$ neutron/$cm^2$s. The ratio of the number of $^{23}$Na and silicon atoms in a silicon sample was calculated as being $0.570(61) \cdot 10^{-12}$.

The study of reactions induced by protons with energies near the threshold and that presents a very small value for the cross-section, order of $\mu b$, is very scarce in the literature. These data can give a better understanding about the formation of the compound nucleus and the existence of structures, clusters, inside the nuclei. In particular, $(p, 2\alpha)$ reactions are usually studied in energies far from the threshold. This situation can be understand taking into account the magnitude of the cross-sections and the experimental difficulties where the presence of few impurities can produce ambiguous data. The nuclide $^{22}$Na (half-life of 2.602 years) originated from the $(p, 2\alpha)$ reaction. The $^{22}$Na decays by electron capture to $^{22}$Ne and it is identified by the characteristic gamma line of 1274 keV.

The energy of the proton beam was monitored by putting a cooper foil in front of the silicon samples. The energy was obtained from the ratio of the $^{62}$Zn and $^{65}$Zn activities coming, respectively, from the $^{63}$Cu$(p, 2n)$ and $^{65}$Cu$(p, 2n)$ reactions. The peaks were fitted using a covariant least-squares method. The results for the proton beam energy and the calculated cross sections are presented in Table 1 for the various silicon foils.

| foil | proton energy (MeV) | cross section ($\mu b$) |
|---|---|---|
| 1 | 23.69(14) | 66(3) |
| 2 | 22.87(14) | 15.4(9 |
| 3 | 22.02(15) | 1.0(4) |
| 4 | 21.20(15) | 25.4(9) |
| 5 | 21.15(15) | 9.0(8) |
| 6 | 19.32(16) | 2.1(5) |
| 7 | 18.96(16) | 4.1(4) |
| 8 | 16.50(18) | 0.92(28) |

Table 1: Results for the cross section of the $^{29}$Si$(p, 2\alpha)^{22}$Na reaction. The first column is the number of the silicon foil and the second is the energy of the incident proton beam.

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## [230] Status of the neutron capture measurement on $^{237}$Np with the DANCE array at LANSCE

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Neptunium-237 is a major constituent of spent nuclear fuel. Estimates place the amount of $^{237}$Np bound for the Yucca Mountain high-level waste repository at 40 metric tons. The Department of Energy's Advanced Fuel Cycle Initiative program is evaluating methods for transmuting the actinide waste that will be generated by future operation of commercial nuclear power plants. The critical parameter that defines the transmutation efficiency of actinide isotopes is the neutron fission-to-capture ratio for the particular isotope in a given neutron spectrum. The calculation of transmutation efficiency therefore requires accurate fission and capture cross sections.

Current $^{237}$Np evaluations available for transmuter system studies show significant discrepancies in both the fission and capture cross sections in the energy regions of interest. Therefore, a measurement of the neutron capture cross section at the DANCE array was proposed. The current status of this experiment will be presented.

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## [233] Measurement of activation cross sections producing short-lived nuclei with pulsed neutron beam

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We measured activation cross sections producing short-lived nuclei with half-lives of less than 10 seconds, which had few experimental reports, by using pulsed d-D neutron beam.

It is difficult for in-beam measurement to measure weak gamma rays owing to high background by prompt gamma rays. Pulsed neutron beam can avoid the influence of prompt gamma rays.

For efficiently measurements of the induced gamma ray of interest, each position of a neutron source, a High Purity Germanium (HPGe) detector, and a sample was needed to optimize. The distance between the neutron source and the HPGe detector has a limitation from the viewpoint of shielded form neutrons. The minimum distance, which could accept the neutron damage of detector, was estimated by using the Monte-Carlo simulation code MCNP4C.

The d-D neutrons were generated by bombarding a water-cooled deuterated titanium target with 350 keV $d^+$-beams at the 80-degree beam line of the Fusion Neutronics Source at the Japan Atomic Energy

Research Institute. The durations of irradiation and measurement were chose to be the same, which was about two half-lives of the induced activity of interest. Samples were located at angles of 0 and 90 degree with respect to the $d^+$-beam that energy of neutron was 3.09 and 2.54 MeV, respectively.

The cross section data of 4 (n, n') reactions ($^{90}$Zr, $^{183}$W, $^{197}$Au, and $^{207}$Pb) with half-lives between 0.8 and 7.8 seconds were obtained. For check the measuring method, the cross section of $^{197}$Au (n, n') $^{197m}$Au reaction was obtained with a pneumatic sample transport system. We concluded that activation cross sections could be measured down to about 100 mb with pulsed neutron in the energy range of 2 to 3 MeV.

In the future, we will measure activation cross sections using pulsed d-T neutron beam.

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## [234] Reliability of prompt $\gamma$-ray intensities for the measurement of neutron capture cross sections

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Neutron capture cross sections of long-lived fission products (LLFP) are needed for a nuclear transmutation technology. Determining the cross sections by using the activation method, if produced nuclei have too long half-lives or are stable, it is difficult. A measuring method by detecting prompt $\gamma$-rays (the prompt-$\gamma$ method) is expected to solve this problem.

It is considered that the comparison with the activation method, which has reliable actual results, can verify the new method. Therefore the cross sections were measured by using the prompt-$\gamma$ method and the activation method, respectively.

Thermal neutron irradiations were carried out by the B-4 neutron guide facility at the Kyoto University Reactor. Since the (n, $\gamma$) reactions of $^{23}$Na, $^{27}$Al, $^{51}$V, $^{55}$Mn, $^{64}$Ni, $^{65}$Cu, $^{141}$Pr, $^{186}$W and $^{197}$Au make the nuclei which half-lives are enough short to measure, the reactions were measured with three 22, 38 and 90% HPGe detectors and a 90% GAMMA-X HPGe detector. The distance from a sample to each detector was 5 cm. A box and plates made of a lithium fluoride were used for shielding from neutrons. The irradiating periods were about 0.4$\sim$3 h.

For nine reactions, the ratios of measured cross section values by the prompt-$\gamma$ method to those by used the activation method were analyzed. The ratios of $^{65}$Cu and $^{186}$W are $-10\%$ and $-25\%$ away from the others, respectively. Those of the other seven reactions were in agreement within 5%. It is clearly seen that the ratios are lower systematically than 1.0 ($\sigma_{prompt}$=$\sigma_{decay}$). It is considered the reason is inaccuracy of the each emission probability of prompt $\gamma$-rays.

We have concluded that the prompt-$\gamma$ method cannot determine (n, $\gamma$) cross section within 10% because precise emission probabilities are not well known. Using more precise emission probabilities of $\gamma$-rays following $\beta$-decay, those of prompt $\gamma$-rays can be determined also.

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## [246] Development of a method of thermal-neutron capture cross section measurement by unfolding prompt gamma ray spectra

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For the transmutation study of radioactive wastes, it is important to obtain precise thermal neutron capture cross sections of long-lived fission products and minor actinides. However, the capture cross sections for some nuclides, have not yet been measured or are poor in accuracy, because they can not be measured by conventional activation methods. Therefore, we have started the development of a method of thermal-neutron capture cross section measurement by unfolding prompt gamma ray spectra. The

cross sections are determined on the basis of energy equivalence between Q-value and an energy sum of cascading gamma rays per a neutron capture reaction. However, prompt gamma ray spectra of isotopes in the medium and heavy mass region, measured with Ge detector, tend to be very complex due to high level densities of compound states. To minimize the error in the unfolding process, a pair-spectrometer system was developed to obtain high peak-to-total spectrum, in which double escape peaks and no compton distribution were clearly enhanced.

In this work, thermal neutron capture cross sections of $^{14}$N and $^{27}$Al were determined by unfolding prompt gamma ray spectra in order to confirm the effectiveness of these methods.

The measurements were carried out using the thermal-neutron guide tube facility in Kyoto University Research Reactor Institute. The neutron flux was about $2*10^7$ n/cm$^2$/s. The pair-spectrometer system, which consists of an n-type Germanium detector and a BGO annulus which is divided into two halves, was used to measure the prompt gamma rays. To estimate and subtract the contribution of background gamma rays generated by scattering neutrons, carbon foils were used. The neutron flux at the sample position was measured by detecting decay gamma rays emitted from $^{28}$Al produced in the $^{27}$Al(n,$\gamma$) reaction. The prompt gamma-ray spectra were obtained in singles, compton suppression and pair-spectrometer modes. To deduce the sum of gamma-ray energies from a raw spectrum of gamma rays, response functions of the detector to gamma rays up to about 10 MeV were calculated by an EGS-4 code. The cross sections of $^{14}$N and $^{27}$Al were determined by deducing the sum of gamma ray energies from unfolded spectra in compton suppression and pair-spectrometer modes. By comparing the present results with evaluated data in JENDL 3.3, the effectiveness of the present method was confirmed.

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## [252] Partial and Double-differential Neutron Scattering Cross Sections from Elemental Titanium at Energies between 8 and 15 MeV

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Precise determination of neutron scattering cross sections is an important basis for improvement of existing neutron data libraries. In the energy range between 7 MeV and 14 MeV, such experimental data are sparce due to the lack of monoenergetic neutron sources. At PTB, the technique for measurement and data analysis was developed in order to fill this "data gap" with precisely determined cross sections.

The neutron scattering cross sections were obtained using time-of-flight (TOF) technique. The measured TOF spectra are simulated using an extensive Monte Carlo code which takes into consideration all relevant details of the experiment. Comparing measured TOF spectra with those simulated with iteratively improved cross sections, uncertainties below 5% can be achieved for differential partial cross sections (DX), and of about 2% for angle-integrated ones.

The method was extended to obtain also double-differential cross sections (DDX). Here, the contamination of the TOF spectra by non-monoenergetic source neutrons has to be corrected for. The parasitic neutron fractions are also simulated, and subtracted. Such simulation is successful only when the underlying data are sufficiently exact. DX from neutron libraries do not fulfil this requirement. Therefore, an additional measurement of data in the energy range below 8 MeV, the energy region of parasitic neutrons, is necessary. Here, a non-monoenergetic neutron source was applied (4-He(d,np) breakup reaction). Using such a continuous neutron source at different incident deuteron energies, the elastic DX below 8 MeV can be exactly obtained, without any approximation.

Using the technique as described above, DX and DDX from elemental titanium were determined at 11 incident neutron energies between 7.95 MeV and 14.72 MeV. As DX, elastic and inelastic (sum of the first levels around 0.9 MeV of 46-Ti and 48-Ti) cross sections were extracted. The other low-lying levels of the five titanium isotopes are superimposed such that an exact classification as partial cross sections is impossible. DDX were then determined in the emission energy range between E-max and 1.5 MeV, E-max being about 1.4 MeV lower than the incident neutron energy.

In this paper, the measurement procedure, data analysis and results will be described in more detail, a comparison of our results with existing experimental data and with neutron libraries will also be discussed.

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## [253] Prompt neutron emission from $^{239}$Pu and $^{235}$U fission fragments

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A series of experiments has been performed to measure the dependence on the fragment mass and total kinetic energy of the average number and energy of prompt neutrons emitted from $^{235}$U and $^{239}$Pu fission fragments in thermal neutron induced fission. The experiments were carried out using neutrons from the PNPI WWR-M research reactor in Gatchina. For $^{239}$Pu target the fragment - neutron correlation measurement was also performed at the first resonance range. In this case the range of the strong resonance at 0.296 eV was selected by Sm filter which was arranged in the neutron flux from the reactor.

The direction-sensitive twin ionization chamber with Frish grids was used for the fission fragment spectroscopy. The prompt neutrons accompanying fission were detected with twelve stilbene crystal which were placed at a distance of 40 cm from the fission chamber. The neutron energy was determined using time-of-flight technique. The time resolution of each neutron detector was estimated as at least not worse 2ns (FWHM) from the width of the prompt gamma-ray peak observed in the time spectrum. The pulse shape discrimination technique was used to separate prompt neutron and gamma - ray events.

The description of experimental set-up and some results of this research are presented in this article.

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## [255] Measurement of the Np-237 Neutron Capture Cross Section from Thermal to 100 eV

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For a study of the incineration of nuclear waste, the transmutation of Np-237 has a first priority due to its amount and activity in a burn-up fuel. The existing limited experimental data on capture cross section of Np-237 in resolved resonance range below $\sim$ 200 eV have been obtained using small efficiency g-ray detectors with or without pulse-weighting technique. Therefore there is obvious necessity in new measurements of neutron capture cross section of Np-237 utilizing another detection technique to improve experimental database for this nucleus.

The present time-of-flight measurements were carried out using the 46 MeV electron Linac of KURRI as a pulsed neutron source and the large 8.54 liter 16-section BGO scintillation detector of JNC as a total energy detector of prompt capture $\gamma$-rays. A newly developed data taking system based on a 40 MHz FLASH ADC enabled to perform the measurements with a highly radioactive 1.1 g sample of Np-237. The capture cross section of Np-237 was measured relative to standard neutron absorption cross section of B-10. Absolute normalization of the capture cross section was carried out using a thermal value obtained from the analysis of Np-237 total cross section measured with the same sample below 1 eV.

The results of neutron capture cross section measurements in the energy range from thermal to 100 eV and total cross section measurements from thermal to 1 eV are presented.

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488 Accurate wave length measurement of high energy gamma-rays from the $^{35}$Cl$(n,\gamma)$ reactions
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## [272] Investigation of activation cross-sections of the proton induced nuclear reactions on natural iron at medium energies

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Iron is one of the most important structural materials in every field of science, technology, industry, etc. Its application in radiating environment requires the knowledge of accurate excitation functions for the possible reactions in question. By using the Thin Layer Activation technique (TLA) the knowledge of such data is also extremely important even in the case of relative measurements the design the irradiation (irradiation energy, beam intensity, duration) and also for radioactive safety estimations. The cross-sections are frequently measured at low energies but there are unsatisfactory and unreliable data in the energy range above 40 MeV.

As a part of our systematic study for medical, industrial and other purposes high purity iron foils were irradiated at the k=110 AVF cyclotron of the Tohoku University, Japan by using the well established stacked foil technique. For degrading the beam energy and for monitoring purposes aluminum and copper foils were also inserted into the stack. The irradiated samples were measured off-line by high resolution gamma/spectrometry. As a result excitation functions for $^{55,56,57}$Co, $^{52,54}$Mn, $^{48}$V, $^{48,51}$Cr, $^{52}$Fe and $^{47}$Sc were deduced and compared with the literature and theoretical calculations.

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## [276] Measurement of activation cross sections of the proton-, deuteron- and alpha particle induced nuclear reactions on platinum

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First motivation for measurements of excitation functions of proton, deuteron and alpha induced nuclear reactions on platinum started with determination the possible impurities in investigation of excitation functions on noble metal targets (Pd, Au, Ir). It was supported further by our wear studies on samples containing significant Pt component ($^{195}$Au,$^{196}$Au). Knowledge of excitation functions has significance for production of medically related radioisotopes ($^{198}$Au,$^{199}$Au, $^{191}$Pt,$^{193m}$Pt,$^{195m}$Pt). Activation data are required for accelerator and target technology and for dose calculations. Production cross-sections and isomeric ratios have importance for reaction mechanism studies.

Searching of the literature practically no earlier experimental activation cross-section data were found. The excitation functions on platinum have been measured by using standard stacked foil irradiation method and high resolution gamma-ray spectroscopy. Thin Pt foils were stacked with Al and Cu and Ti monitor foils and irradiated at the cyclotrons of the Tohoku University (proton) and of the Vrije Universiteit Brussel (proton, deuteron and alpha). Several stacks were irradiated by covering overlapping energy ranges for the Pt targets. Large number of the monitor foils makes possible to follow the beam intensity and the energy degradation along the whole stack via the monitor reactions ($^{nat}$Al(p,x)$^{22,24}$Na, $^{nat}$Cu(p,x)$^{56,58}$Co,$^{62,65}$Zn, $^{nat}$Ti(d,x)$^{48}$V, $^{nat}$Cu($\alpha$,xn)$^{66,67}$Ga,$^{65}$Zn).

Direct and cumulative cross-sections were calculated from the parameters of the bombarding beam, of the target and the corresponding decay data. As a result: experimental cross-sections, derived integral yields and activation curves will be reported and compared with the theoretical calculations performed by the Alice-IPPE code for the following reactions:

$^{nat}$Pd(p,x) $^{191,192,193,194,195,196m,196g,198g}$Au, $^{188,189,191,195m}$Pt, $^{189,190,191}$Ir up to 70 MeV

$^{nat}$Pd(d,x) $^{192,193,194195196m,196}$Au, $^{191,195m,197}$Pt, $^{189,192}$Ir up to 21 MeV

$^{nat}$Pd($\alpha$,x) $^{191m,191g,192,193m,193g,195m,195g,197m,197g}$Hg,
$^{192,193m,193g,194,195m,195g,196m,196g,198m,198g,199,200m}$Au,$^{195m,197m,197g}$Pt up to 38 MeV

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## [278] Measurement of the $^{58}$Ni(n,t)$^{56}$Co, $^{59}$Co(n,p)$^{59}$Fe and $^{63}$Cu(n,$\alpha$)$^{60m+g}$Co Reaction Cross Sections from 14 to 20 MeV

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Studies of excitation functions of fast-neutron induced reactions are important for testing nuclear models and in a wide range of applications such as fission and fusion reactor technologies and proposals for accelerator driven systems (ADS) [1,2]. Nevertheless, for many reactions, especially in the energy range above 15 MeV the cross sections data are either sparce or discrepant. The hydrogen and helium production cross sections on Co, Ni and Cu as a structural materials are of particular importance for the estimation of the material damage and handling limits. Activation cross sections are needed to determine the induced long-lived radionuclides whose decay activities impact the scenario of waste management and materials recycling. One of the major radionuclides of importance to the medium-term waste management consideration is $^{60}$Co.

New results were obtained for the $^{58}$Ni(n,t)$^{56}$Co, $^{59}$Co(n,p)$^{59}$Fe $^{63}$Cu(n,$\alpha$)$^{60m+g}$Co activation reaction cross sections in the energy range from 13.3 to 21 MeV. The measurements have been performed in response to the request of the EAF Working Group on Evaluation Processing, Validation and Benchmarking. The irradiations were carried out at the 7MV Van de Graaff accelerator at IRMM, Geel. Quasi-mono-energetic neutrons with energies between 13.3 and 20.6 MeV were produced via $^{3}$H(d,n)$^{4}$He reaction at 1, 2, 3, and 4 MeV incident deuteron energy. All reaction cross sections measured in the present work are referenced to $^{27}$Al(n,$\alpha$)$^{24}$Na standard reaction cross section. Neutron flux spectra were determined using neutron-spectrum information obtained by time-of-flight method and spectral index method that involves various monitor reactions with distinct energy thresholds. Standard $\gamma$-ray spectrometry was employed for measurement of radioactivity. Corrections have been applied for sample irradiation and counting geometry, beam intensity variation during irradiation, background neutrons, neutron absorption and scattering, $\gamma$-ray absorption and $\gamma$-ray sum coincidences. For more details about the method see Ref. 3.

The measurment results are compared with work by other authors, current evaluated data files and new model calculations.

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2) Y. Ikeda, J. of Nucl. Sci. and Technol., Supplement 2, (August 2002), 13-18.
3) A. Fessler et al., Nucl. Sci. Eng. 134, 171 (2000)

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## [281] Cross sections of the proton induced nuclear reactions on iridium

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Excitation functions of proton induced nuclear reactions on iridium were measured for practical applications up to 70 MeV. No earlier experimental data were found in the literature. The work was performed in the frame of a systematic study of excitation functions of light charged particle induced nuclear reactions on metal targets in the medium energy range. The cross-sections on iridium have been measured by using a standard stacked foil irradiation method. The irradiations were carried out with low intensity external beams of the cyclotrons at the Tohoku University, Sendai and of Vrije Universiteit Brussel. Al and Cu foils were inserted into the stack as energy degraders and to monitor the beam parameters. The $\alpha$-spectra of the irradiated iridium and monitor foils were assessed non-destructively on a High purity Ge detector. Counting was started a few hours after EOB and continued for several weeks. This allows following the decay of isomers and parent radionuclides and decomposition of gamma-lines originating from different isotopes. The beam intensity and the energy degradation along the stack were controlled via the $^{nat}$Cu(p,x)$^{56,58}$Co,$^{62,65}$Zn and $^{nat}$Al(p,x)$^{22,24}$Na monitor reactions. So called elemental

cross-sections were calculated by supposing the target to be monoisotopic. Direct and cumulative cross-sections were deduced from the parameters of the bombarding beam and of the target taking into account the decay data of the radionuclides involved. As a result the cross-sections of the $^{nat}$Ir(p,xn)$^{188,189,191}$Pt and $^{nat}$Ir(p,x)$^{186,187,188,189,190,192}$Ir nuclear reactions up to 70 MeV are presented for the first time . The measured experimental data were compared and analyzed with theoretical calculations based on the model code Alice-IPPE. The physical yields for production of different Pt and Ir radioisotopes were calculated from the experimentally measured excitation functions and the stopping powers for pure Ir metal. Application of the measured experimental data in the practice will be discussed.

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## [292] A report on the achievements of subgroup 19 on Activation Cross Sections of the WPEC, OECD-NEA

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Subgroup 19 on Activation Cross Sections of the Working Party on Evaluation Cooperation of the OECD-NEA has recently concluded its activities. The goal of the subgroup was to generate a large set of new measured activation cross sections relevant to nuclear applications and make these data available to the nuclear science community. In addition, modeling efforts and sensitivity studies were undertaken to evaluate the use of measured data and model calculations for the prediction of unknown cross sections. The latter addresses the potential of model calculations to satisfy issues on the High Priority Request List when no measured data are available. In the course of the activities of the subgroup over ninety reaction channels were studied experimentally. All except the most recent of these data have been compiled into Exfor format by members of the subgroup and submitted to OECD-NEA. As a result most of these data can now be retrieved online from the data centers. A systematic comparison was made with the new evaluated data files JEF3.0/EAF2003, JENDL3.3 and ENDF/B-VI.8 and with the current status of the global parameter systematics of the model code Talys. In addition, a considerable number of locally optimized parameter sets were developped. Both the global and local approaches emphasize the use of consistent physics modelling for all important reaction channels and nuclides involved in the decay. Comparison of the two approaches allows to assess the effort required when model estimates to a certain accuracy must be made. Parameter sensitivity studies were undertaken to further assess the accuracy requirements on model parameters if target uncertainties for the cross sections have been specified. The value of this approach has demonstrated itself and indicates the need for model codes that fit all available experimental data in order to connect the data covariance with the covariance of the model predictions. The work of the subgroup was a joint effort between IRMM, ANL, FZ-Jülich, INRNE Sofia, NIPNE Bucharest, IEP and Atomki Debrecen, JAERI, and Tohoku University. A comprehensive review of the subgroup activities will be presented.

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## [302] UNFOLDING NEUNRON INDUCED REACTION CROSS-SECTIONS AT ENERGY BELOW 50 MEV

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At Kiev Isochronous Cyclotron some experiments to unfolding the neutron cross section by activation method in energy region up to 50MeV were made. Unfolding spatially - energy performances of neutron fields obtained at deuterons energies $E_d$=30MeV and $E_d$=40MeV measured at 0, 15, 30, 45 and 60 degree axis of beam are presented in this article. However, on energy region more than 20MeV some data require now essential improvement. For definition of neutron cross sections at Kiev Isochronous Cyclotron "U-240" we carried out two series of experiments. The radiant of neutrons were served Beryllium (Be) with a target of a total absorption, which was irradiated with deuterons with energies $E_d$=30MeV and $E_d$=40MeV /reaction $^9$Be(d,n)$^{10}$B/. Obtaining of cross sections was carried out by a method of activation

foils in a neutron field. The packages of the foils placed at angles: 0, 15, 30, 45 and 60 degree axis of deuteron beam at 25 cm from Beryllium target. The threshold nuclear reactions of activation (where cross section are known with high accuracy) were selected so that their responses in a spectrum overlapped all explored energy regions. A detector foils (Na, Ti, Fe, Al, Ni, Tl, Au, Nb, Co, Zr) were interleaved by monitor Ni foils. Measured activity of the foils placed at all angles used to restore spatially - energy performances of neutron fields at $E_d$=30MeV and $E_d$=40MeV. The restored neutron spectrums later were used for deriving neutron cross sections. The obtained neutron spectrums under all angles at $E_d$=30MeV and $E_d$=40MeV after smoothing were used for restoration of neutron cross sections known with poor precision. Besides, the cross-sections of $^{203}$Tl(n,2n)$^{202}$Tl, $^{58}$Ni(n,np)$^{57}$Co, $^{59}$Co(n,$\alpha$) and other reactions also were unfolded. They differ from those known earlier but are in a good agreement with some experimental data and with calculations of the Japanese scientists.

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## [303] Measurement of double differential cross sections of fragment-production by tens of MeV particles

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Fragments which are secondary particles heavier than $\alpha$-particle, cause a large local ionization. Therefore, the energy and angular doubly differential cross-section data (DDX) for fragments production are important for dosimetry and evaluation of radiation effects in devices or instruments, such as single event upset (SEU) by cosmic rays. Up to now, however, experimental data of the fragment production are very scarce due to experimental difficulties of the detection. Thus, almost all past experimental data were obtained by the activation method that did not provide energy and angle information. Furthermore, theoretical calculation treating fragment production is very few. Therefore, it is important to accumulate reliable experimental DDX data for fragment production.

For fragment detection, we adopted 1) a Bragg curve spectrometer (BCS) providing various information with a single counter and 2) an energy-time of fight (E-TOF) method having the capability of mass identification in almost whole energy region for a charged particle beam.

For 1), the present BCS was designed with special care to apply not only to a charged particle beam but also a neutron beam, and resulted in success to obtain light fragments by proton and neutron induced reactions. In particular, BCS proved very promising for fragments detection in neutron-induced reaction, while there are still some problems that should be solved.

For 2), we have fabricated a chamber for measurements and starting measurements. For a start detector of TOF, we will employ a MCP (multi-channel plate) coupled with a thin Al film having good time resolution and low energy loss for fragments. For a stop detector (E detector), MCP and SSD which has good energy resolution will be adopted. The scattering chamber was designed to enable simultaneous measurements of BCS and E-TOF. The combination of these methods proved very powerful for the measurement of fragments induced by charged particles.

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## [321] INCLUSIVE SPECTRA OF REACTIONS $^{56}$Fe(p,xp),(p,x$\alpha$)

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The inclusive spectra of protons and a-particles emitted from proton induced reactions on $^{56}$ Fe isotopes at Ep=29.9±0.1MeV in angular range 30–135 ° with the step 15° have been measured on isochronous cyclotron U-150M of Institute of Nuclear Physics. Typically, intensities between 40 and 180 nA have been utilised with a beam energy resolution of 0.3%. The self-supporting isotopic enriched (95%) foil of $^{56}$ Fe with thickness 2.7 mg/cm$^2$ in these experiments has been used. The standard method of two-detector telescope system (DE-E) registration of secondary particles has been applied. The experimental twice-differential and partial cross-section of the reactions $^{56}$Fe(p,xp),(p,x$\alpha$) were measured.

Basing on exciton model of pre-equilibrium decay have been calculated spectra of multi-step direct (MSD) and compound (MSC) processes for both reactions on $^{56}$ Fe. This code uses the Griffin exciton model for pre-equilibrium nuclear reactions to describe the emission of particles with mass numbers of 1 to 4 from an equilibrating composite nucleus. A distinction is made between open and closed configurations in this system and between the multi-step direct and multi-step compound components of the pre-equilibrium cross sections. Additional MSD components are calculated semi-empirically to account for direct nucleon transfer reactions and direct knock-out processes involving cluster degrees of freedom. Evaporation from the equilibrated composite nucleus is included in the full MSC cross section. Output of energy differential and double differential cross sections is provided for the first particle emitted from the composite system.

From comparison of experimental and calculated integral spectra it is follows that main contribution in experimental cross section is due to MSD reaction mechanism.

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## [341] $^{48}$Ti$(n, xn\ yp\ z\alpha\ \gamma)$ reactions for neutron energies up to 250 MeV

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Cross section measurements were made of prompt $\gamma$-ray production as a function of neutron energy induced by fast neutrons on $^{48}$Ti. Partial gamma-ray cross sections for transitions in $^{45-48}$Ti, $^{44-48}$Sc, $^{42-45}$Ca, $^{41-44}$K, and $^{41-42}$Ar have been determined. Energetic neutrons were delivered by the Los Alamos National Laboratory spallation neutron source located at the LANSCE/WNR facility. The prompt reaction $\gamma$-rays were detected with the large-scale Compton-suppressed germanium array for neutron induced excitations (GEANIE). Neutron energies were determined by time of flight technique.

$\gamma$-ray excitation functions were converted to partial $\gamma$-ray cross sections taking into account the dead-time correction, the target thickness, the detector efficiency, and the neutron flux (monitored with an in-line fission chamber). The data will be presented for neuton energies between 1 to 250 MeV. These results were compared with model calculations [1] which include compound nuclear and pre-equilibrium emission.

[1] R.D. Hoffman, Private communication

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## [345] Measurements of Fission Cross Section of Actinides with the FIC detector at the n_TOF Facility

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Trans-Uranium elements (TRU) such as Np, Pu, Am and Cm are built up as a result of multiple neutron captures and radioactive decays in the presently operating nuclear reactors based on the U/Pu nuclear fuel cycle. Several proposals have been made to reduce the radiotoxicity of nuclear waste containing TRU. They all rely on neutron induced capture and fission of the TRU, in particular of $^{237}$Np, $^{241,243}$Am, and $^{244,245}$Cm. It is clear that any kind of waste burner system, will need to be loaded with

fuel containing a large fraction of TRU. The response of these systems (e.g. criticality conditions) to the presence of TRU is directly linked to the knowlegde of the fission and capture cross sections of the mentioned TRU isotopes.

The weakly damped beta-vibrational states in secondary well of the potential barrier are responsible for resonance-like structures, observable if energy resolution is good enough. For the sub-barrier nucleii very pronounced vibrational resonances have been observed between 0.1 and 2 MeV where the n_TOF neutron energy resolution allows us to study the fine structure of vibrational resonances.

With these basic motivations, the n_TOF Collaboration has performed neutron induced fission cross section measurements of $^{233,4,6}$U, $^{237}$Np, $^{241,3}$Am, and $^{245}$Cm relative to $^{235,8}$U using the the parallel plate ionization chamber (FIC) as a fission fragment detector. A total of 16 targets and 18 electrodes are mounted together, leaving gaps of 5 mm between layers. The analysis of the recently obtained results is presented.

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## [350] Investigation of Formation of Residual Nuclei from $^{nat}$U by Reactions with 660-MeV Protons

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Natural uranium targets were irradiated by a proton beam with energy 660-MeV in the Phasotron accelerator in Laboratory of Nuclear Problems in Joint Institute of Nuclear Research in Dubna, Russia. Cross-sections for the formation of residual nuclei were determined by gamma-spectrometry. Due to the large amount of residual nuclei they are divided (for processing purposes) into three half-life groups - long-lived (> 100 days), intermediate (100 days > $T_{1/2}$ > 1 days), and short-lived (< 1 day). The irradiation was performed in two parts - a short irradiation of one uranium target (5 min) and a longer irradiation of the second one (27 min) both with an intensity of approx. 2 $\mu$A. There was also third uranium target which was placed 30 cm perpendicular from the beam in the plane of the first and second targets and which was irradiated by background neutrons. The uranium targets had diameters of 15 mm weighted ca 164 mg. High quality HPGe detectors provided measurements of gamma rays. The measurement of the first uranium target started 12 min after irradiation to intent on measurement of short-lived nuclei; the second one was used to determine long-lived isotopes. To exactly monitor the beam the aluminum targets were used. Measurements of long-lived isotopes were carried out for two years. Total number of ca 150 spectra was analyzed; it means approximately 40,000 gamma lines to identify. Until now were successfully observed (with cross-section determination) ca 25 long-lived isotopes, ca 45 intermediate-lived isotopes, ca 120 short-lived isotopes and 11 isotopes from neutron induced reactions in the third (by background neutrons irradiated) target. Experimental results are compared with modern computation codes results. Until now were calculated theoretical predictions by codes CEM2k+GEM2, LAQGSM+GEM2, CEM2k+GEMINI, LAQGSM+GEMINI, INCL+ABLA. The final data will be also compared with theoretical simulation using codes those were developed within the HINDAS project.

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## [356] Study of 660-MeV Proton-Induced Reactions on $^{129}$I

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Isotopically enriched $^{129}$I targets (85% $^{129}$I and 15% $^{127}$I) were exposed to a beam of 660-MeV protons at the JINR DLNP Phasotron and a total of 75 residual products were obtained by radiochemistry. In the present work, we perform an extended comparison of our experimental data with ten different models, realized in eight codes: LAHET (Bertini, ISABEL, and INCL (Cugnon-Schmidt) options), CASCADE, CEM95, CEM2k, LAQGSM+GEM2, CEM2K+GEM2, LAQGSM+GEMINI, and CEM2k+GEMINI. The comparisons are performed according to the well known standard methods. Out of 75 measured reaction cross section, only 48 are found to satisfy the criteria necessary to be used. Average deviation factor and its standard deviation were used for the comparison. We found that most of the codes are fairly reliable in predicting cross sections for nuclides not too far away in mass from iodine, but differ greatly in the deep spallation region. The best agreement with the data, especially in the A=40-90 region, is shown by the codes CEM2k and LAQGSM when they are merged with the GEMINI code.

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## [366] Measurement of $^{235}$U Fission Neutron Spectra Using a Multiple Gamma Coincidence Technique

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The Los Alamos Model [1] predicts the shape of the fission neutron energy spectrum for incident primary neutrons of different energies. Verifications of the model normally are limited to measurements of the fission neutron spectra for energies higher than that of the primary neutrons because the low energy spectrum is distorted by the admixture of elastically and inelastically scattered neutrons. This situation can be remedied by using a measuring technique that separates fission from scattering events. One solution consists of using a fissile sample so thin that fission fragments can be observed indicating the occurrence of a fission event. A different approach is considered in this paper. It has been established that a fission event is accompanied by the emission of between seven and eight gamma rays, while in a scattering interaction between zero and two gammas are emitted, so that a gamma multiplicity detector should supply a datum to distinguish a fission event from a scattering event. We processed as follows: A subnanosecond pulsed and bunched proton beam from the UML Van De Graaff generates nearly mono-energetic neutrons by irradiating a thin metallic lithium target. The neutrons irradiate a $^{235}$U sample. Emerging neutron energies are measured with a time-of-flight spectrometer. A set of four $BaF_2$ detectors is located close to the $^{235}$U sample. These detectors together with their electronic components identify five different events for each neutron detected, i.e. whether four, three, two, one, or none of the $BaF_2$ detectors received one (or more ) gamma rays. The theory underlying this approach has been published [2]. We present the results of our fission neutron energy spectra.

[1]. D. Madland and J. Nix, Nucl. Sci. Eng. 81, 213,(1982)
[2]. C. Ji, G.H.R. Kegel, J.J. Egan, D.J. DeSimone et al, J. Nucl. Sci. and Tech. Supplement 2, 815(2002)
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## [382] Neutron Scattering Cross Section Measurements for Tm-169 via the (n, n') Technique*

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The neutron physics group at the University of Massachusetts Lowell (UML) has been involved in a program of scattering cross section measurements for highly deformed nuclei such as Tb-159, Tm-169, Th-232, U-235, U-238, and Pu-239. Ko et al.[1] have reported neutron inelastic scattering data from Tm-169 for states above 100 keV via the (n,n'$\gamma$) reaction at incident energies in the 0.2 MeV to 1.0 MeV range. In the present paper we report direct (n,n') measurements of neutrons scattered from Tm-169 in the 0.2 to 1.0 MeV range. The time-of-flight method was employed. It requires that our 5.5 MeV Van de Graaff accelerator be operated in the pulsed and bunched beam mode producing subnanosecond pulses at a 5-MHz repetition frequency. Neutrons are produced by the Li-7(p,n)Be-7 reaction using a thin metallic elemental lithium target. For cross-section determination, the (n,n') method is more reliable since the scattered neutrons are directly measured. However in cases where the level density of the nuclei is high, the accurate determination of the cross section of each level by (n,n') becomes very difficult due to the conflict between neutron energy resolution and neutron yield. The current measurements obtained via the (n,n') technique are complementary to the (n,n'$\gamma$) measurements.

[1] Y. J. Ko et al., Nuclear Physics A679, 147-162 (2000).

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## [383] Measurement of Neutron-Production Double-Differential Cross Sections for Continuous-Energy-Neutron-Incidence on Fe and Pb by Liquid Organic Scintillator

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Nuclear data in the intermediate energy region are required for programs of accelerator driven transmutation system, radiotherapy, and space development. Neutron production cross section measurements for proton incidence have been studied in wide energy range to get reliabilities of model calculations, or to improve nuclear reaction models. However, it has been difficult to get their reliabilities for neutron-incident data. Neutron-incidence cross section data are very scarce in the intermediate energy region. The purpose of this study is to measure neutron-production double-differential cross sections for neutron-incidence in the wide intermediate energy range.

The experiment was performed at WNR facility in Los Alamos Neutron Science Center (LANSCE). Incident neutrons were generated from the spallation-neutron-source that allowed inclusive neutron-incidence measurement. The flight path from the spallation target to the sample was about 90 m. Fe and Pb were selected as samples. The fission chamber was set in front of the sample to obtain the number of incident neutrons. To detect emitted neutrons NE213 liquid organic scintillators (127 mm thick and 127 mm in diameter) were arranged at 15°, 30°, 60°, 90°, 120°, and 150°. NE102A plastic scintillators of 10 mm thick were also set in front of NE213 detectors to eliminate charged-particle events. Along with those experiments, spallation neutrons were directly induced into the NE213, and response functions were also measured for all NE213s used in this study.

To determine incident neutron energy, time-of-flight technique was used on the assumptions that the total time-of-flight was exhausted only by incident-neutron. To discriminate neutron and gamma-ray events, the two-gates charge integration method was adopted. Emitted neutron spectra were determined

by unfolding charge-integration spectra with response functions of the neutron detector. Because neutron detectors were not large enough to differentiate neutron energy above about 120 MeV in respect to charge-integration, data analysis was performed up to around this energy. Results were compared with calculations by the GNASH code.

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## [417] Experimental technique for measurement of (*n*,*xn*) double-differential cross sections for incident neutron energies above 100 MeV

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In progress of intermediate energy proton-accelerator technology, a highly intense neutron source by spallation reactions becomes usable for scientific researches and industrial developments. Accelerator-Driven-Systems (ADS) for energy production and long-lived nuclear-waste transmutation have been proposed. The research and development thereof have raised the practical need for neutron nuclear reaction data such as neutron-incident neutron production ($n$,$xn$) double differential cross sections (DDX) in the intermediate energy region. Some experimental data of ($n$,$xn$) DDX were reported for incident neutron energies above 20 MeV. These measurements were conducted by using the monoenergetic neutron beam. However, the experimental data have never been obtained above 100 MeV because of the lack of the monoenergetic neutron field.

The experimental technique for measurement of ($n$,$xn$) DDX for incident neutron energies above 100 MeV for a natural lead has been developed with continuous-energy neutrons up to 400 MeV. Incident neutrons were produced in the spallation reaction by the 800-MeV proton beam at Los Alamos Neutron Science Center (LANSCE) in Los Alamos National Laboratory (LANL). The energies of incident neutrons were determined by the time-of-flight method. The neutron flux was monitored by a fission ionization chamber. Emitted neutrons were detected by the recoil proton method. The radiator was a 20-mm thick polyethylene disk. We also performed measurements with a carbon disk to eliminate the contribution of carbon reaction. A phoswich detector consisting of a NaI(Tl) and NE102A plastic scintillators was used for detecting recoil protons to detect the recoil protons as full stop events. A veto counter was set in front of the radiator to eliminate the charged particles from the sample. The veto counter was 10-mm thick NE102A plastic scintillator. The d$E$ counter was located between the radiator and the phoswich detector to identify the charged particles produced in the radiator. The d$E$ detector was a 5-mm thick NE102A plastic scintillator. The distance between the sample and the phoswich detector was about 0.7 m.

The emitted neutron energy is almost equal to the energy of recoil proton when the recoil proton is produced by elastic scattering. The neutron energy spectra were unfolded by the FERDO code. The response function of detector system was measured by use of continuous-energy neutrons at WNR facility. We compared the experimental cross section data with the calculations by the Particle and Heavy Ion Trasnport code System (PHITS) and JAERI version of Quantum Molecular Dynamics (JQMD) codes in order to check the applicability of this experimental technique.

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## [432] Destruction and neutron capture cross sections with a high spin K-isomeric target of $^{177m}$Lu

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High spin K isomeric targets are very interesting to study the induced decay of nuclear states. The techniques used to produce a $^{177m}$Lu (23/2-) target consist of an isotopic separation, an irradiation and a chemical separation. The huge neutron flux ($1.8\times10^{15}$ n cm$^{-2}$ s$^{-1}$) of the Grenoble ILL reactor was used to produce the Lu isomer by the $^{176}$Lu(n,$\gamma$) reaction. Thanks to this experiment, we were able to estimate the destruction cross section of the $^{177m}$Lu for the first time. This cross section was also measured directly with the target of $^{177m}$Lu. Neutron capture cross section measurements were achieved at the reactor (Saclay) and at the ILL reactor. These measurements allow to evaluate the $^{177m}$Lu isomer super-elastic scattering cross section. The results of these experiments will be shown in this talk.

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## [433] Binary and Ternary Fission of $^{252}$Cf Investigation with Gammasphere

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New method of fission process investigation had been originated in our works more than 10 year ago, and it was evolved all this time. It is based on the spectroscopy of the correlated $\gamma$-rays emitted by a pair of fission fragments and by the light charged particle, in case of a ternary fission event. The method allows to extract the data of a new kind about fission process that are inaccessible by the other methods. Among these data we can mark the yields of correlated fission fragment pairs, distributions on neutron multiplicity for the different charge split of the fissile nucleus. Using these data we could restore the distribution of the excitation energy of primary fission fragments which are formed at the scission point, before their deexcitation by neutron evaporation.

Concerning ternary fission, beside usual kinematical characteristics of the light charged particles, which were estimated starting from their lowest kinetic energy, we estimated the populations of the ground and first excited states in $^{10}$Be. This allowed us to estimate directly the neck temperature near the scission point which equals $1.0 \pm 0.1$MeV.

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## [444] Neutron Spectra from Intermediate-Energy Nucleus-Nucleus Reactions

Hiroshi Iwase [1], Yoshiyuki Iwata[2], Takashi Nakamura [3], Konstantin K. Gudima[4], Stepan G. Mashnik[5], Arnold J. Sierk[6], Richard E. Prael[7]

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Double-differential cross sections of neutron production at angles from 0 to 110 degrees from many reactions induced by light and medium nuclei on targets from $^{12}$C to $^{208}$Pb, at several incident energies from 95 to 600 MeV/nucleon have been measured recently at the RIKEN (Institute of Physical and Chemical Research) Ring Cyclotron in Japan and at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Science, Japan using the time-of-flight technique. We have analyzed all these new measurements using the Quantum Molecular Dynamics (QMD) model, the

Oak Ridge intranuclear cascade model HIC, the ISABEL intranuclear cascade model from LAHET, and the Los Alamos version of the Quark-Gluon String Model (LAQGSM). On the whole, all four models used here describe reasonably well most of the measured neutron spectra, although different models agree differently with data from specific reactions and some serious discrepances are observed for some reactions. We present here some illustrative results from our study, discuss possible reasons for some of the observed discrepancies and try to outline ways to further improve the tested codes in order to address these problems.

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## [445] $^{148}$Gd Production Cross Section Measurements for Accelerator Target Facilities

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In a series of experiments at LANSCE's WNR facility, $^{148}$Gd production was measured for 600- and 800-MeV protons on tungsten, tantalum, and gold. These experiments used 3 mm thin W, Ta, and Au foils and 10 mm thin Al activation foils. Spallation yields were determined for many short-lived and long-lived spallation products with these foils using gamma and alpha spectroscopy.

The production of $^{148}$Gd by 800-MeV protons on thick tungsten targets is of great importance to spallation neutron facilities at LANSCE (WNR's target 4 and MLNSC's target 1), because of the limits placed by DOE on the acceptable 148Gd inventory allowed in the target before requiring the facility to be defined as a "nuclear facility." Allowed isotopic inventories are particularly low for this isotope because it is an alpha-particle emitter. The activity level of 148Gd is small, but it encompasses almost two-thirds of the total dose burden in the LANSCE facilities based on present yield estimates.

The upper tungsten target at the Lujan Center and Target 4 at WNR are both approximately 7 cm in length. An 800-MeV proton loses approximately 200 MeV energy in passing through these targets, thus exiting with an energy of approximately 600 MeV. Given that DOE limits the amount of $^{148}$Gd production, a better understanding of the true production rate in tungsten targets was needed. This is the motivation for measuring the cross section at 600 and 800 MeV. The measured cross sections are compared with the LANL codes MCNPX and CEM2k+GEM2.

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## [455] Indirect measurements of cross sections via Trojan Horse Method

Claudio Spitaleri[1], Silvio Cherubini[2], Antonio Del Zoppo[3], Alessia Di Pietro[3], Agatino Figuera[1], Agatino Musumarra[1], Maria Grazia Pellegriti[1], Rosario Gianluca Pizzone[1], Stefano Romano[1], Claus Rolfs[4], Aurora Tumino[1], Marisa Gulino[1], Angelo Rinollo[1], Salvatore Tudisco[1], Carmen Bonomo[3], Marco La Cognata[5], Livio Lamia[5]

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Accurate knolowledge of termonuclear fusion reaction rates is crucial in pure and applied physics. Due to the precence of Coulomb barrier, the reaction cross section $\sigma$(E)nuclear drops exponentially with decreasing center-mass energy E. However, for nuclear reactions studied in the laboratory, the target and projectile orbital electron crouds produce a screening potential U$_e$: For $E/U_e > 1000$ schielding effects become important and experimental data show an exponential enhancement of the astrophysical S(E)factor, as observed in several fusion reaction. Experimental $U_e$ values are usually extracted by comparing the electron-shielded $S_s$(E) with $S_b$(E), obtained from direct measurements. These $U_e$ value are systematically much larger than the expected ones, deduced in the adiabatic limit. The Trojan Horse Method [THM] can be applied to determine the energy dependence of $S_b$(E), without the effects of the Coulomb barrier and electron screening. Indeed, if quasi-free mechanism conditions are fulfilled, this method allows the extraction of $S_b$(E) by measuring the cross section of a proper three body process. In this way it is possible to determine $U_e$. The basic features of the THM are discussed togheter with

a review of recent applications, aimed to extract the bare nucleus astrophysical $S_b$(E) factors for several two-body processes.

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## [468] Partial Gamma-Ray Cross Sections for Neutron-Induced Reactions on Stable Germanium Isotopes

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Using separated isotopes of $^{70}$Ge, $^{72}$Ge, and $^{74}$Ge, we have measured gamma-ray partial cross-sections for neutron-induced reactions on each of these nuclei using the GEANIE detector array at the LANSCE/WNR spallation neutron source. The key to this measurement is removal of "false" cross section resulting from neutrons scattering off the HPGe detectors rather than the Ge target. The method of accounting for this will be presented, and interesting results will be given.

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## [470] Excitation Functions of Products from $^{208,207,206,nat}$Pb and $^{209}$Bi (p,x) Reactions Measured in the 40–2600 Energy Range and Predicted Theoretically

Yury E. Titarenko[1], Vyacheslav F. Batyaev[1], Valery M. Zhivun[1], Evgeny I. Karpikhin[1], Alexander B. Koldobsky[1], Ruslan D. Mulambetov[1], Svetlana V. Mulambetova[1], Yury V. Trebukhovsky[1], Sergey L. Zaitsev[1], Konstantin A. Lipatov[1], Stepan G. Mashnik[2], Richard E. Prael[2]

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The excitation functions of independent and cumulative yields of residual products in thin lead and bismuth targets irradiated with protons from 40 MeV to 2.6 GeV measured recently at ITEP, Moscow, are presented and compared with theoretical results by the Los Alamos codes LAHET, CEM2k, and LAQGSM, both last merged with an improved version of the Furihata's Gereralized Evaporation-fission Model (GEM2), with the Liege code INCL merged ABLA evaporation-fission model, with the JINR, Dubna, code CASCADE, and with the phenomenological systematics by Silberberg, Tsao, and Barghouty realized in the code YIELDX.

The predictive power of the tested codes is different but it was found to be satisfactory for most of the nuclides in the spallation region and some fission products, though none of the benchmarked codes agree well with all the data in the whole mass region of product nuclides at all measured energies, and all codes should be improved further. On the whole, the predictive power of all codes for products in the spallation and in the middle of the fission region is better than at the border between spallation and fission and betweeen fission and fragmentation regions; therefore, development of better models for fission and fragmentation is of first priority.

The work has been performed under the ISTC Project #2002 supported by the European Community and was partially supported by the U. S. Department of Energy and the NASA ATP01 Grant NRA-01-01-ATP-066.

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## [488] Accurate wave length measurement of high energy gamma-rays from the $^{35}$Cl$(n,\gamma)$ reactions

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Despite the improvement of related fundamental constants, and the subsequent re-evaluation of energy calibration standards, the calibration of gamma-ray detectors still remains a problem at high energies. While neutron capture on $^{35}$Cl offers a series of regularly spaced gamma lines up to about 8.5 MeV and the cross-section is also sufficiently large, precise energies have been measured with the state of art doubly flat crystal spectrometer, GAMS4, only for a small fraction of the potentially useful gamma lines. In particular, the only high-energy line measured is the 6111 keV gamma ray. Because this gamma ray is a member of a multiplett structure, its high precision energy value is not useful in HPGe energy calibrations.

The goal of our recent wave length measurements of gamma rays from the $^{35}$Cl$(n,\gamma)$ reactions at GAMS4 facility is two fold:

a) To provide precise energies for a set of well-selected gamma rays for energy calibration at neutron capture gamma-spectrometer facilities.

b) To determine more precise neutron binding energies based on recent $(n,\gamma)$ measurements at the Budapest PGAA facilities.

Two RbCl targets were put near to the reactor core of the High Flux Research Reactor, Grenoble, France. As usual, we re-measured the previously determined gamma-ray energies for calibration reasons coming from $^{35}$Cl neutron capture reactions. The energies of the 517-, 786-, 1165-, 1951- and 6111-keV transitions were re-measured at a few times $10^{-7}$ precision. Furthermore we have measured the most intense high-energy decay cascades of

$$7790 \text{ — } 888 \text{ keV}$$
$$7414 \text{ — } 1165 \text{ keV}$$

with a precision of few times $10^{-6}$. The corresponding level energies and the binding energy have been determined from a least-square fit. Three different cascades define the neutron binding energy and its calculated energy values show an agreement within 1 sigma level.

The obtained new energy values are used to recalibrate the gamma ray energies from our $(n,\gamma)$ measurements at the Budapest PGAA facilities. The impact of these new energy values on the binding energies will be demonstrated.

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# Poster B

**Zia**, Tuesday 15:30–17:30

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269 Evaluation of Nucleon-induced Cross Sections on Magnesium and Silicon Isotopes up to 3 GeV
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330 New nuclear data evaluations for Ca, Sc, Fe, Ge, Pb, and Bi isotopes
*Arjan J. Koning, Marieke C. Duijvestijn, Steven C. van der Marck, Robin Klein Meulekamp, Alfred Hogenbirk*

## [4] Optical Potentials for Evaluating Data for Nuclear Processes Involving Alpha Particles*

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A prescription to obtain alpha-nucleus global optical model potential for use to study the nuclear processes involving alpha particles in the entrance and exit channels has been developed. Both the phenomenological and microscopic approaches have been used to determine the alpha-nucleus optical potential. Use has been made of the well-behaved quantities of the nuclides like (i) the volume intergral, (ii) the mean squared radius, (iii) the radius at which the Wood-Saxon potential is 2.4 MeV, and (iv) the slope of the potential at that radius. These quantities for real as well as imaginary potentials are related to the corresponding parameters ($V_0$, $R$ and $a$) of the Wood-Saxon form of the potential. From the systematics of these quantities observed for nuclides of varied mass numbers over a range of alpha energies, the parameters for real as well as imaginary parts of the optical potential are self-consistently obtained for a specific nucleus at a given alpha energy. This potential has been validated in many cases in predicting the angular distribution of the elastically scattered alpha particle at different energies, the energy distribution of the outgoing alpha particle in HI reactions and also by the cross section evaluation for nuclear reactions where alpha is in entrance or exit channel.

*Work is done under IAEA sponsored CRP on Reference Input Parameter Library (RIPL).

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## [55] A New Approach for Nuclear Data Covariance Generation

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Nuclear data covariance information is required to assess uncertainties in design parameters in reactor applications. The error estimation of calculated quantities relies on uncertainty information reported in the basic nuclear data libraries such as the US Evaluated Nuclear Data Library, ENDF/B. The uncertainty files in the ENDF/B library are obtained from analyses of experimental data and are stored as variance and covariance. As is well known, the data representation in the ENDF library is in tabular format (for instance, cross sections as a function of energy) or represented as set of resonance parameters together with a nuclear formalism (for example, the cross section representation in the resonance region using the Reich-Moore representation). The objective of this paper is to describe a methodology developed at Oak Ridge National Laboratory (ORNL) for the generation of resonance parameter covariance matrices in the resonance region, and the methodology developed at Los Alamos National Laboratory (LANL) for the generation of covariance matrices in the higher-energy regions.

At ORNL, data evaluations in the resolved and unresolved resonance region are performed with the computer code SAMMY. The SAMMY evaluation in the resolved resonance region uses the R-matrix formalism, and in the unresolved range the evaluation is based on Hauser-Feshbach theory. Resonance parameters are obtained by fitting the experimental data using the generalized-least-squares technique from which the parameter covariance matrix is determined.

In a SAMMY evaluation, experimental data such as transmission data (or the corresponding effective total cross sections), capture cross sections, and/or fission cross sections are evaluated by taking into account the uncertainties in the experimental data. Various sources of experimental uncertainties exist, including normalization, background, time-of-flight, flight-path length, sample thickness, temperature, etc. All of these uncertainties are included in the evaluation process in order to properly determine the resonance parameter covariance matrix.

At LANL, the methodology for generating covariance data consists of least-squares fitting and model parameter adjustment. The least-squares fitting method calculates covariances directly from experimental data. The parameter adjustment method employs a nuclear model calculation such as the optical model and the Hauser-Feshbach model, and estimates a covariance for the nuclear model parameters.

In the full paper, both the ORNL methodology for generating the resonance parameter covariance matrices in the resolved and unresolved resonance region and the LANL scheme in the high energy region will be described. These methods have been applied to generate covariance data for Gadolinium isotopes $^{152}$Gd, $^{154}$Gd, $^{155}$Gd, $^{156}$Gd, $^{157}$Gd, $^{158}$Gd, and $^{160}$Gd, respectively. The resulting covariance data have

been effectively processed and used in benchmark calculations. Results of those benchmark calculations will also be reported.

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## [71] Neutron- and Proton-Induced Nuclear Data Evaluation of Minor actinides for Energies up to 250 MeV

Young-Ouk Lee[1], Jonghwa Chang[1], Tokio Fukahori[2], A.Yu. Konobeyev[2]

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Within the frame work of the JENDL high energy library, the evaluation of neutron- and proton nuclear data for thorium-232, U-233,234,236, and Cm-243,244,245,246 isotopes have been performed at energies up to 250 MeV. Neutron data was evaluated at energies from 20 MeV to 250 MeV, and combined with the JENDL-3.3 data at 20 MeV, while proton data was obtained for energies from 1 to 250 MeV.

Nuclear model parameters are largely based on the IAEA-RIPL recommendation, and adjusted to better reproduce the available measurements. Special attention was paid on the neutron fission cross sections to achieve continuity and consistency with the existing JENDL-3.3 evaluation using theoretical model, experimental fission barriers, and appropriate fittings. The coupled channel optical model was applied to calculate the total, reaction, elastic, and direct inelastic cross sections, and to obtain the transmission coefficients. Decay of excited nuclei was described with the Hauser-Feshbach and exciton models using the GNASH code to simultaneously handle neutron, proton, deuteron, triton, helium-3, alpha, gamma emissions and fissions. Primary pre-equilibrium emission spectra of helium-3 and alpha-particles were calculated with the coalescence pick-up model using the ALICE/ASH code, and fed into the GNASH calculation. Particles and gamma emission spectra after fission were calculated based on the the statistical approach of Fong, and adjusted to the experimental data using the ALICE-ASH code.

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## [72] A new systematics of fragment mass yields from neutron induced fission of actinides at neutron energies above 5 MeV.

Dmitriy M. Gorodisskiy, Sergey I. Mulgin, Alexandr Y. Rusanov, Sergey V. Zhdanov

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The mass and energy distribution in the proton induced fission of compound nuclei $^{234,236,237,239}$Np, $^{239,240,241,243}$Am, $^{245}$Bk at proton energy $E_p = 10.3$ MeV; $^{234,236,237,239}$Np, $^{240,241,243}$Am at proton energy $E_p = 22.0$ MeV; $^{233}$Pa and $^{236}$Np at $E_p = 7.4 - 30.0$ MeV have been measured by the spectrometry of coincident fission fragments with surface-barrier detectors.

The experimental information obtained have been analyzed in the framework of a new-developed method of multicomponent analysis, which is free from any assumptions about the shapes of the mass distributions of distinct modes [1].

The results of the analysis allowed to study the basic characteristics of distinct modes in their dependence on the incident particle kinetic energy and nucleonic composition of fissioning system.

Revealed regularities in the behavior of fission modes, such as isotopic invariance of fragment charge distributions from asymmetric fission of actinides [2], have been used for developing a new systematics of the pre- and post neutron emission fragment mass yields from fission of target nuclei from Th to Bk in reactions with protons and neutrons at kinetic energies from 5 to 200 MeV. This systematics reproduces main features of the experimental data with good accuracy and could be used as a basis for the calculations of fission product yields in reaction with neutrons in energy range 5 – 200 MeV in the interests of transmutation of minor actinides.

The systematics has been realized as the computer code PYF.

References

[1] S.I. Mulgin et al., Phys. Lett., B 462 (1999) 29.
[2] D.M. Gorodisskiy et al., Phys. Lett. B 548 (2002) 45.

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## [73] Evaluation of cross sections for neutrons and protons up to 3 GeV on $^{12,13}$C

Yukinobu Watanabe[1], Weili Sun[2], Kazuaki Kosako[3], Efrem S. Sukhovitskiĭ[4], Osamu Iwamoto[5], Satoshi Chiba[5], Tokio Fukahori[5]

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High-energy neutron and proton nuclear data for carbon are requested with high priority in various applications, such as shielding design of accelerator facilities, dose evaluation in cancer therapy with neutron and proton beams, efficiency calculation of neutron detectors, and nucleosynthesis prediction of light elements, Li, Be, and B. We have performed an evaluation of cross sections on $^{12,13}$C for both neutrons and protons in the incident energy range extended up to 3 GeV in order to meet the above nuclear data needs. The evaluation is based on predictions from nuclear model calculations and systematics as well as measurements. A nuclear model calculation code system is developed using the GNASH code for energies below 150 MeV and the JQMD code for those above 150 MeV. The evaluated cross sections contain the following data: neutron total cross sections, nucleon elastic scattering cross sections and angular distributions, non-elastic cross sections, production cross sections and double-differential cross sections of secondary light particles ($n$, $p$, $d$, $t$, $^3$He, $\alpha$, and $\pi$), and isotope production cross sections. The results are compared with available experimental data and the LA150 evaluation. For validation of these nuclear data, thick-target neutron production spectra from carbon target are calculated for bombardment of 113 MeV and 256 MeV protons using the MCNPX transport code and are compared with the measurements. These evaluated nuclear data are included into the JENDL high-energy file.

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## [75] $^{231}$Pa and $^{233}$Pa neutron-induced fission data analysis

Vladimir M. Maslov[1], Mamoru Baba[2], Akira Hasegawa[3], Nikolai V. Kornilov[4], Alexander B. Kagalenko[4], Natalia A. Tetereva[1]

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Neutron-induced fission data for $^{233}$Pa nuclide are of much interest for the thorium fuel cycle development. Measured data base is comprized only from two data sets [1, 2, 3], which do not seem to be fully compatible. Application of Hauser-Feshbach statistical model for the analysis of neutron-induced fission data [1, 2] and $^{233}$ Pa(n,f) fission data [3], extracted from the transfer reaction $^{232}$Th($^3$He,p)$^{234}$Pa would be of much interest. Above emissive fission threshold fission probabilities of $^{233}$Pa and $^{232}$Pa nuclides, fissioning in $^{233}$Pa(n,nf) and $^{233}$Pa(n,2nf) reactions, respectively, could be estimated using data of transfer reactions $^{232}$Th($^3$He,d)$^{233}$Pa and $^{231}$Pa(d,p)$^{232}$Pa [4]. First chance fission cross section is estimated based on consistent description of $^{238}$U(n,f), $^{238}$U(n,xn) and $^{232}$Th(n,f), $^{232}$Th(n,2n) data. This aproach could be validated in case of $^{231}$Pa(n,f) neutron-induced fission data analysis. Data on fission of residual nuclides, emerging in transfer reactions $^{231}$Pa(d,p)$^{232}$Pa, $^{230}$Th($^3$He,d)$^{231}$Pa and $^{230}$Th($^3$He,t)$^{230}$Pa are used for the $^{231}$Pa(n,f)data analysis up to 20 MeV. Data by Kobayashi et al. [5] below fission threshold of $^{231}$Pa(n,f) reaction are used to fix fission barrier parameters.

This analysis of Pa fission data is the major constraint for other neutron cross sections and secondary spectra evaluation for the $^{231}$Pa and $^{233}$Pa data files. $^{231}$Pa and $^{233}$Pa data files are compiled. Average unresolved resonance parameters, fast neutron cross sections, angular distributions and secondary neutron spectra differ very much from the previous evaluations.

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## [76] $^{233}$U neutron data evaluation

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Uranium-233 is the main fissile nuclide in uranium-thorium-fueled nuclear reactors. It turns out that fission data description within a Hauser-Feshbach approach maintains major constraint for the $^{233}$U capture, neutron elastic and inelastic scattering, (n,2n), (n,3n) reaction cross sections and secondary neutron spectra evaluation. Absolute fission data at $E_n$ ~3 MeV and $E_n$ ~15 MeV are fitted. The rigid rotator optical model potential is obtained based on total cross section and elastic and inelastic angular distribution. Consistency of optical model calculations with recent total data by Guber et al. is investigated [1]. Consistent estimate of capture and fission data is obtained up to $E_n$ ~1 MeV. Prompt fission neutron spectra (PFNS) were calculated with the model which takes into account contribution of neutrons, emitted in (n,xnf) reaction. Local minima of average PFNS energies at $E_n$ ~7 MeV and $E_n$ ~12 MeV are predicted.

$^{233}$U evaluated data file is compiled. Average unresolved resonance parameters, fast neutron cross sections, angular distributions and secondary neutron spectra differ very much from previous evaluations.
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## [80] Calculation of reaction cross sections for several actinides

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Based on experimental fission yield and cross section data, new, self consistent, neutron-induced reaction cross section calculations for $^{235,238}$U, $^{237}$Np and $^{231,232,233}$Pa have been performed.

The statistical model code STATIS was improved to take into account the multi-modality of the fission process. The three most dominant fission modes, the two asymmetric standards I (S1) and standard II (S2) modes and the symmetric superlong (SL) mode have been taken into account. De-convoluted fission cross sections for those modes for $^{235,238}$U(n,f) and $^{237}$Np(n,f) based on experimental branching ratios, were calculated for the first time up to the second chance fission threshold. For $^{235}$U(n,f) and $^{233}$Pa(n,f), the calculations being made up to 20 MeV incident neutron energy, higher fission chances have been considered. This implied the need for additional calculations for the neighbouring isotopes.

As a side product also mass yield distributions could be calculated at energies hitherto not accessible by experiment. Experimental validation of the predictions is being envisaged.

The most intriguing results will be presented.

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## [82] Calculation of prompt neutron multiplicities and spectra for several actinides

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The prompt fission neutron multiplicity and spectra of actinides are nuclear data of crucial importance. Based on experimental fission yield and total kinetic energy data, new calculations for the prompt neutron multiplicity and spectra for $^{235,238}$U(n,f), $^{237}$Np(n,f) in the incident neutron energy range up to 20 MeV and for $^{252}$Cf(SF) have been performed.

For the first time the multi-modality of the fission process was taken into account. Additionally, for some isotopes a more realistic fission fragment residual temperature distribution as well as an anisotropy of the prompt neutron emission led to improved agreement between the calculation and experimental results. Also the range of fission fragment pairs entering in the multiplicity and spectrum model was extended over the entire experimental fission fragment mass range. This led to an improved version of the Los Alamos model and especially to an improved determination of the input model parameters.

The results of the calculations will be presented.

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## [107] Nucleon Pick-up and Stripping Experiments and New Data on Nuclear Subshells

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Methods for physical information extracting from any experiment data are based usually on relationships of a definite degree of generalization. Combining of two or more experiments data via more general relations gives a group of complementary experiments. Connecting each other of such experiments data help to overcome information limitation of data obtained by ordinary way. Really it means a removing of systematic deviations caused by assumed model dependence from data. Such procedure can be treated as a new virtual experiment. As a result information evaluated becomes more accurate both in statistical and more general meaning: physical information becomes more put in accordance to the objective reality.

Some special employments of this conception were developed.

In nucleon pick-up and stripping experiments on the same nucleus nuclear level spectroscopic factors (SF) are obtained by taking into account definite view of the nuclear potential in target nucleus and nucleon-nucleus interaction for incident nucleus. Meanwhile, one can connect sums of SF using quantum mechanics sum rules only. These sum rules allow one to obtain more realistic SF normalization and make definite conclusions on total momentum transferred for each SF. The stated ideas underlie to the base

of the method of putting nucleon pick-up and stripping experiments data in accordance to each other. Some essential results were obtained /1/.

Exclusion of systematical disagreements between results of various photonuclear experiments was achieved using the sum (g,xn) = (g,n) + 2(g,2n) as more general relation connecting data for reactions (g,xn), (g,n) and (g,2n) /2/. Producing of definite linear combinations or solving of system of linear equations including known and unknown data gave new information not obtained till now. An example is joint evaluation /3/ of (g,xn), (g,n) and (g,2n) reactions cross sections for 19 nuclei from $^{51}$V to $^{238}$U.

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Data on even-even Ca isotopes shell structure (nucleon occupation probability and energy values of single-particle orbits) were obtained from the analysis of the pick-up, stripping and level spin-parity data. Data from ENSDF (Evaluated Nuclear Structure Data File) databank /1/ were used mainly. The method of putting nucleon pick-up and stripping experiment data in accordance to each other /2,3/ was applied.

It was found out that subshell energy dependences on mass number show that processes of the forming the new shell 1f7/2 in these nuclei are analogous for both neutrons and protons. In nuclei of $^{40,42}$Ca the 1f7/2-subshell is a part of the higher 1f2p-shell, in $^{44,46,48}$Ca 1f7/2 is placed in the middle of the energy gap between 1f2p and 1d2s-shell, so this subshell forms a separate shell with number 28 as a magic one. In further nuclei (Ti, Cr, Fe etc.) this structure is remaining and hence number 28 continues to be magic one for these nuclei.

The inversion of the proton 1d3/2 and 2s1/2 orbits in $^{48}$Ca isotope relative to remaining isotopes is discovered. This peculiarity explains irregularities in spin-parity values of ground states of nuclei of K: $^{39,41,43,45}$K ground states have a $J\pi = 3/2+$, but $^{47}$K - 1/2+. To describe the 1d3/2 - 2s1/2 proton inversion in $^{48}$Ca it was supposed that spin-orbit splitting decreases in this nucleus. This hypothesis was tested in the dispersion optical model calculations for $^{40,42,44,46,48}$Ca /4/ and it was cleared that this assumption allows describing this inversion correctly.

Proton occupation probability values are close to classical shell model values for all isotopes studied, but neutron occupation probability values- only for double magic nuclei of $^{40,48}$Ca. For remaining isotopes noticeable deviations were obtained, the most significant - for the middle isotope $^{44}$Ca.

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The dependency of energy values of first $J^\pi = 2^+$ states on neutron number in $^{90,92,94,96}$Zr isotopes demonstrates two clear maxima at N = 50 and N = 56. N = 50 is a well-known magic number. To explain N = 56 maximum neutron and proton subshell energy and occupation probability values on neutron number were investigated systematically for $^{90,92,94,96}$Zr isotopes. All data under discussion were obtained from one-nucleon transfer (pick-up and stripping) reactions and spin-parity data. Information from ENSDF databank /1/ was used mainly. The method of joint one-nucleon transfer reaction data analysis /2,3/ was applied.

From the energy values analysis it was found out that the neutron $2d_{5/2}$-subshell in $^{96}$Zr becomes to look like a separate shell (similarly to $1f_{7/2}$-subshell in $^{48}$Ca). Investigation of the proton occupation probabilities of $1g_{9/2}$ orbit in isotopes of Zr revealed that the structure reconstruction takes place in $^{96}$Zr so that this nucleus becomes harder and probably more spherical in comparison with neighbors. Such peculiarities are known to be corresponding to magic nuclei, and therefore the conclusion that N = 56 is a magic number for Z = 40 can be done.

Some very impressive similarities of $^{96}$Zr and $^{48}$Ca exist:

- both neutron and proton numbers of one nucleus are twice as those for another;
- both nuclei decay via the same quite rare mode $2\beta^-$;
- half-life times differ by factor 2: $T_{1/2}(^{96}\mathrm{Zr}) = (2.1 +0.8\ (\mathrm{stat}) -0.4\ (\mathrm{stat}\ ) \pm 0.2\ (\mathrm{syst}))\times 10^{19}$ years /4/, $T_{1/2}\ (^{48}\mathrm{Ca}) = (4.2 +3.3 -1.3) \times 10^{19}$ years /5/.

All these facts can be explained if to suppose the existence of additional interaction between Z=20 and N=28 closed structures in nuclei of $^{48}$Ca and $^{96}$Zr. Connection between these structures can be destroyed with some probability giving $2\beta^-$ decay of $^{48}$Ca with appropriate half-life time. From this point of view in $^{96}$Zr the same "20–28" connections are presented twice, and therefore $^{96}$Zr $2\beta^-$ decay must have half-life time less by factor exactly 2 in comparison to $^{48}$Ca.

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## [109] THE METHOD OF PUTTING NUCLEON PICK-UP AND STRIPPING EXPERIMENTS DATA IN ACCORDANCE TO EACH OTHER

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It is known that nuclear state spectroscopic factors extracted from nucleon pick-up and stripping reactions data are characterized by large degree of systematic uncertainty. It takes place because of significant uncertainties in absolute normalization of spectroscopic factors and besides because of ignorance of some j values of the total transferred moments. As a result absolute values of the spectroscopic factors obtained in various experiments can differ by factor 2 and more.

The method of spectroscopic factors evaluation with taking into account systematical disagreements mentioned was developed. The main idea is to correct the experimental pick-up and stripping reaction data in order to satisfy three conditions: - strong sum rules would fill out for 3 single-particle orbits closest to Fermi energy, experimental data for which are presented with maximum of completeness; - non-strong sum rules would fill out for the rest orbits; - total number of the nucleons for the all orbits should be conserved.

To achieve this aim several freedom degrees are used: new normalization for experimental data is introduced S+nlj(Ex) →(n+)(S+nlj(Ex)), S-nlj(Ex) → (n-)(S-nlj(Ex)); all known information on spin of the final states is used, and all possibilities are investigated for states with unknown spins. The computer codes ARES were developed on the base of the described procedures.

As a result, more realistic spectroscopic factors allow avoiding of discrepancies between pick-up and stripping experimental data. Nucleon occupation probabilities of single-particle orbits and single-particle energies are determined on the base of improved spectroscopic factors.

Nucleon occupation probabilities and single-particle energies of single-particle orbits were determined on the base of improved spectroscopic factors for $^{40,42,44,46,48}$Ca, $^{46,48,50}$Ti, $^{50,52,54}$Cr, $^{54,56,58}$Fe, $^{58,60,62,64}$Ni, $^{64,66,68,70}$Zn, $^{90,92,94,96Z}$r, $^{116,118,120}$Sn both for neutron and proton orbits /1, 2/. Many essential results were obtained, some new phenomena were found-out /3, 4/.

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## [115] The Evaluation of Gamma Ray Emission Probabilities in the Decay of $^{56}$Co

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$^{56}$Co is a radioactive source that is particularly useful for the calibration of gamma ray detector efficiencies, as it provides a number of gamma rays of usable strength with energies up to 3.5 MeV. The gamma ray emission probabilities in the decay of $^{56}$Co have been evaluated as a contribution to the International Atomic Energy Agency's Coordinated Research Programme on "X- and Gamma-Ray Decay Data Standards for Detector Calibration and Other Applications". Data published in 31 papers between 1965 and 2002 for 45 gamma rays with energies between 263 keV and 3612 keV have been reviewed. Discrepancies within the data abound and this paper reports on the use of several procedures to evaluate these discrepant data. It will be shown that the application of different evaluation philosophies can produce similar recommended values. An additional problem encountered in these data is the assumption by some authors of a linear extrapolation for their log-log detector efficiency curves for energies above about 2.5 MeV.

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## [116] Half-Life Evaluations for $^{3}$H, $^{90}$Sr and $^{90}$Y

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A recent paper [1] has reviewed methods for the evaluation of discrepant sets of data and demonstrated the results of applying these methods to the published half-life data of $^{90}$Sr and $^{137}$Cs.

The half-life data for $^{3}$H has been subject to a comprehensive review and critical evaluation by Lucas and Unterweger [2]. The current paper reports the results of applying the various evaluation procedures of ref. [1] to the data of ref. [2], resulting in a recommended half-life of 4497(4) days.

Ref. [1] highlighted problems in the evaluation of the discrepant half-life data of $^{90}$Sr, in particular the worrying upward trend in the data, where the weighted mean of all the measurements increases, on average, by 35 days each time a new measurement result is added. The current paper reports on further analyses of this data.

New measurements of the half-life of $^{90}$Y have been reported by Kossert and Schrader [3]. This has prompted a new evaluation of all available published $^{90}$Y half-life data. The data is fairly consistent and a value of 64.063(16) hours is recommended.

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## [119] Treatment of Data Uncertainties

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For analysis of data using either Least Squares or Bayes' Equations (generalized Least Squares), it is necessary to provide appropriate and accurate information regarding the uncertainties on those data. If the data are correlated, then covariances must be provided to the analysis code, and properly incorporated into the fitting procedure. At present, a number of competing methods exist both for generating such covariance matrices and for making use of them. There is no universal consensus as to which methods are correct, nor is there sufficient understanding regarding the consequences of the choices.

In this paper, the generation and use of data covariance matrices will be discussed within the context of the analysis of neutron-induced cross section data via the R-matrix code SAMMY. Two complementary

approaches will be described, the first involving mathematical manipulation of Bayes' Equations, and the second utilizing computer simulations.

In the first approach, Bayes' Equations are applied to the raw data (counts per time channel). While it is seldom practical to calculate directly the quantities measured in an actual time-of-flight experiment, nevertheless it is possible to formally express Bayes' Equations in this manner. Further, because raw data are uncorrelated, there is no ambiguity in the treatment of covariances in these equations. The equations are expressed in terms of two distinct types of parameters, those related to the theory (the R-matrix parameters) and those related to the data (the normalizations, backgrounds, and other corrections required in converting from raw to reduced data). The equations are then mathematically transformed (using matrix algebra) and rewritten into different but equivalent equations expressed in terms of reduced data (cross section as a function of energy). The rewritten equations produce results (updated parameter and covariance matrix) exactly equivalent to those which would be produced if one could fit directly to the raw data.

Examination of those equations leads to a definition of the (reduced) data covariance matrix whose use will give results consistent with those given by the analysis of raw data. Essentially, the data covariance matrix must be expressed in terms of the theoretical cross sections, not in terms of the measured cross sections.

Results of the mathematical approach will be confirmed by the second approach: a series of computer simulations will be performed via SAMMY, using a variety of techniques (some of which are correct and others which are not). The simulations will explore the extent to which erroneous results will be obtained by using incorrect/inexact methods.

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## [125] Photonuclear data and modern giant resonance physics

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The aim of this work is to try to attract the attention of the photonuclear data experts to recent results in giant resonance (GR) physics and to propose an idea for parametrization GR, which is especially necessary for astrophysics[1] and for unstable nuclei.

GR physics was developing very quickly in the 80-th and at the beginning of the 90-th ("GR physics renaissance"). The largest changes were probably just for the resonances which are of greatest interest for photonuclear data, namely, for the isoscalar E2, isovector M1 resonances and, relatively recently, for the low-lying E1 strength, the co-called pygmy dipole resonance (PDR). (See also the contribution to this conference by Kamerdzhiev, Kovalev and Litvinova).

Beginning from the known review of Bertrand [2], the experimental parametrizations and systematics of the GR data were based , as a rule , on the estimations by Landay and Eliashberg obtained within the infinite Fermi liquid theory, namely the resonance mean energy and width are proportional to $A^{-1/3}$ and $A^{-2/3}$, respectively. However, in the recommended libraries RIPL1 and RIPL2 the very large value 4 MeV of the M1 resonance width was recommended for all nuclei and for the isoscalar E2 resonance a linear A-dependence was used. The situation with the temperature dependence of the E1 strength has changed drastically as compared with the $T^2$ Fermi liquid dependence.

The large-scale QRPA calculations of E1 strength [3] for about 6000 nuclei have shown that, in order to explain the PDR properties, it necessary to go beyond the QRPA theory and,in authors' opinion, to add a contribution of more complex configurations with phonons.

Taking into account , in addition, the necessity of nuclear data for unstable nuclei [1] one can propose the FOLLOWING PROCEDURE FOR THE CALCULATIONS AND SUBSEQUENT PARAMETRIZATION OF PHOTONUCLEAR DATA. It is necessary to use a consistent microscopic theory [4] for non-magic nuclei[5] with universal interaction parameters which takes simultaniously into account all three known mechanisms of GR damping: the single-particle continuum (to describe properties of light and medium weight nuclei and dripline nuclei), the QRPA contribution and the phonon coupling, which explains one half of the GR width in stable nuclei [4]. After corresponding GR calculations for some selected nuclei it is necessary to parametrize the results as a function of N and Z in order to obtain the GR and PDR parameters suitable for other nuclei or several groups of nuclei. This parametrization should be suitable for unstable nuclei also or at least for some groups of them. In princple, it is desirable to develope a variant of the microscopic theory with all the above-mentioned GR formation mechanisms which would be completely selfconsistent. Such a theory is in progress now. The procedure proposed is a rather labour-intensive one and underdeveloped technologically but at present it is fully realistic.

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## [132] Fission Products Evaluation for ENDF/B-VII

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The neutron cross section data of 21 high priority fission products were submitted for a new release of ENDF/B-VII. The evaluation work was motivated by the need to improve ENDF/B-VI for materials of importance for a number of applications, such as criticality calculations for spent fuel storage design, high burn-up fuel design and reactor core design. In particular, improved neutron capture cross sections in the keV energy range are important in a reactor design. Many fission products in a reactor core have large neutron capture cross sections both in thermal and keV energy region. In most cases, considerable improvement over the current ENDF/B-VI files was achieved in capture and other reaction channels.

From the recent BNL review, re-evaluation was done in the fast energy region using EMPIRE[1] and merged with the evaluated resonance part[2] in the unresolved energy to make full data set. If necessary, background was put in the total, elastic and capture cross sections. Also, the general rule for the merge was established. The nuclear data full set involves (n, tot), (n, n), (n, n'), (n, 2n), (n, 3n), (n, na), (n, np), (n, g), (n, p) and (n, a) cross sections from thermal to 20 MeV. General description (MF=1) was completed for each nucleus. The results showed good agreement with the measured data and continuity at the merging energy. Format and physics checking codes were applied and NJOY code was run to check the individual cross sections and the processing. The new evaluation results will contribute for better applications.

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## [136] ON PARAMETRIZATION OF THE ISOVECTOR M1 RESONANCE AND NATURE OF THE PYGMY DIPOLE RESONANCE IN SPHERICAL NUCLEI

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We discuss the characteristics of the isovector M1 and pygmy dipole resonance (PDR) concerning the nuclear data evaluation on the base of modern giant resonance physics. (See also the motivation of the work in the contribution to this conference by S.Kamerdzhiev).

1. We have parametrized the most reliable experimental data for the M1 resonance in $^{208}$Pb [1] using the Lorentz resonance shape and the least squares method. It was obtained that the resonance width $\Gamma = 0.36$ MeV which is in sharp contrast to the value $\Gamma = 4$ MeV recommended for all nuclei botn in the RIPL-1 (1998) and in RIPL-2 (2002). A noticeable difference between experimental and recommended width values has been also obtained for several other nuclei. We propose other methods to parametrize M1 resonances based on microscopic approaches.

2. During last decade much interest has been spent on the investigation of the PDR [2,3]. One of the main motivation was that the corresponding nuclear structure information is of great astrophysical interest [3,4].

We have calculated for the first time the PDR within two microscopic approaches, namely, the Extended Theory of Finite Fermi Systems (ETFFS) [5.6] and its partial case, i.e. the Continuum Quasiparticle Random Phase Approximation (CQRPA), for three stable and unstable tin isotopes $^{120}$Sn, $^{104}$Sn and $^{132}$Sn. The principal difference between the ETFFS and CQRPA is that the former takes into account the phonon coupling while the latter does not. It was obtained that the inclusion of the phonon coupling increases within the factor of 2-4 the E1 strengths summed in the (0-$< E >/2$) energy interval, where $< E >$ is the mean energy of the GDR, and also it increases very noticeably the strengths summed in the (0-12) MeV interval for all the nuclei considered. A reasonable description of the GDR characteristics including their widths was obtained too.

We can conclude that accounting for the phonon coupling is necessary for the description of the PDR in any microscopic approach. Because the ETFFS has universal parameters of the Landau-Migdal interaction and account for the single-particle continuum and the phonon coupling, the use of the ETFFS gives a possibility at present to try to calculate and parametrize the PDR and other photonuclear data for many spherical nuclei including the drip-line ones.

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## [191] Fitting and updating gamma-ray energies

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Experimental values of physical quantities are, often, correlated. Since correlation coefficients are related to variances and covariances, covariance matrices must be taken into account in every step of a fitting procedure. Also, covariance matrices are necessary to update values every time new experimental results are obtained or some quantities correlated to those values are changed.

In this contribution we show the Least Squares Method design matrix which takes into account the cross-over relations, recoil energies, and the dependence on the fundamental constants. The formulas are applied to the experimental data related to gamma-ray energies given in ref. [1] by using the procedure described in ref. [2].

Since gamma-ray energies (in eV) are related to some fundamental constants (Planck constant, speed of light, elementary charge, and the Si lattice parameter), the obtained gamma-ray energies must be updated to the 1998 CODATA recommended values [3] (in ref [4] the procedure was applied just to the $^{198}$Au and $^{192}$Ir gamma-ray energies).

Using the experimental information quoted in ref. [1] we fitted 329 standard gamma-ray energies updating them to the 1998 recommended fundamental constants. The covariance matrix of the gamma-ray energies and the related fundamental constants was directly obtained from the procedure.

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## [193] New Resonance Parameter Evaluation of Cl Neutron Cross Sections

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Better measurements and evaluations are needed for many elements where the existing evaluations or the underlying nuclear cross section data are not sufficiently accurate for reliable calculation of criticality safety margins. Chlorine is an important element in applications where chlorides are present in significant amounts; for example, polyvinyl chloride pipe is 57% Cl by weight. Deficiencies in the existing ENDF/B-VI data evaluation for Cl led to our resonance parameter evaluation of Cl neutron cross sections in the resolved resonance region with the multilevel Reich-Moore R-matrix formalism. Our evaluation takes advantage of recent high-resolution capture and transmission measurements at the Oak Ridge Electron Linear Accelerator (ORELA) as well as older total cross section measurements at Karlsruhe (KFK) to extend the resolved resonance energy range to 1.2 MeV with much more accurate representation of the data than previous evaluations.

Resonance analyses were carried out with the computer code SAMMY, which utilizes Bayes' method, a generalized least squares technique. Doppler and resolution broadening, multiple scattering corrections, and other effects were taken into account. Analysis of the available $^{35}$Cl(n,p)$^{35}$S cross section data was

facilitated by the SAMMY capability to compute charged-particle penetrabilities for the proton exit channel.

Our resonance parameter representation describes the data much better than does ENDF/B-VI, and it should lead to improved criticality safety calculations for systems where Cl is present. In the paper we discuss the cross section data, resonance analysis, results, and parameter uncertainties.

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## [214] $^8$Be nuclear data evaluation

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An R-matrix analysis of experimental nuclear data on the reactions $^4$He$(\alpha,\alpha)$, $^4$He$(\alpha,p)$, $^7$Li$(p,\alpha)$, $^7$Li$(p,p)$, $^7$Li$(p,n)$, $^7$Be$(n,p)$, $^6$Li$(d,\alpha)$, $^6$Li$(d,p)$ and $^6$Li$(d,n)$ leading to the $^8$Be intermediate state has been completed over the last two years. The excitation energy above the $^8$Be ground state has been brought up to at least 22–24 MeV for all reactions except $^4$He$(\alpha,\alpha)$ and $^7$Be$(n,p)$. More than 4000 data points are included. The data for the reaction $^4$He$(\alpha,\alpha)$ do not fit well, but the other six reactions fit with a reasonable $\chi^2$/(point). Most of the resonances found in the R-matrix analysis correspond to resonances formerly known from experiment. There are at least 18 resonances in this analysis. Integrated $^4$He$(\alpha,p)$, $^7$Li$(p,\alpha)$, $^7$Li$(p,n)$, $^6$Li$(d,\alpha)$, $^6$Li$(d,p)$ and $^6$Li$(d,n)$ cross sections are presented and compared with nuclear data.

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## [215] Experimental Validation of the Crystal Lattice Model in the R-Matrix Code SAMMY

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In the evaluation of low energy cross-sections, the broadening of neutron resonances due to the motion of the target nucleus at the atomic scale has been thorougly studied. The simplest model for Doppler Broadening is the Free Gas Model (**FGM**) that neglects atomic interaction between the target nuclei present in a sample. When the target atoms are bound to a molecule or a crystal, the incident neutron energy can change the atomic vibrational or rotational quantum state and a more realistic treatment is needed. Lamb [1] in the early days of cross-section theories derived a theoretical expression to account for the presence of chemical binding in a crystal sample. This model, known as the Crystal Lattice Model (**CLM**), accounts for the emission or absorption of phonon (quantum of vibrational energy) and expresses the capture cross-section as a function of the weighted spectrum of the lattice vibration frequencies.

This model was recently implemented in the bayesian R-matrix fitting computer code SAMMY [2]. SAMMY is widely used in the analysis and evaluation of cross-section data in the thermal, resolved and unresolved range. Based on the DOPUSH program [3], the phonon expansion method is used to compute the CLM Doppler broadening function.

In the present work, the Crystal Lattice Model of SAMMY is tested against transmission experiments performed at GELINA on U238 [4]. These experiments have been carried out to study Doppler broadening of neutron resonances at low temperature where the chemical binding effects can be easily detected. The measurements were performed with U and $UO_2$ samples at 23.7K and at room temperature. It is shown in this work that the Crystal Lattice Model of SAMMY well reproduces the assymetrical shape of the experimental transmission spectra in the vicinity of the 6.7 eV, 20.9 eV and 36.7 eV resonances. This paper also suggests several extensions in the present CLM model to remove some current approximations .

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## [238] Statistical Treatment of Nuclear Level Schemes and Spin Cut-off Parameter

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Recently, extensive level schemes have been established * which are complete in a given energy and spin range and which contain reliable spin and parity assignments. This level scheme together with neutron resonance data represents an ideal prerequisite in order to test statistical theories and to determine statistical parameters below the neutron binding energy.

In the present work the energies, spins and parities of hundreds of level schemes are applied to determine the spin cut-off factor for low lying levels as a function of atomic mass number, A. A balance number of even-even, even-odd and odd-odd, light, medium heavy and heavy, spherical and deformed nuclei are considered in this investigation. We have found that unlike the claims made by some authors, the spin cut-off factor does not follow a smooth A dependence and also deviates substantially from their corresponding rigid body values. We reported already some preliminary results at the recent APS meeting (DNP) October, 2003.

Level density parameter has also been obtained using this data and its dependence on A, on pairing energies and shell effects are determined. We have shown that the level density parameter near the major shells is very different than their corresponding experimental values. This can be accounted for by considering pairing interactions and shell effects as well. We have initiated such an investigation, the results will be presented and discussed.

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## [247] Evaluations of K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni and Zn for JENDL-HE

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In recent year, high-energy nuclear data are required for various applications of accelerators and space development. Proton data as well precision as neutron data are necessary in these high-energy applications. Medium-heavy nuclei are very important for radiation shielding and structure material of accelerators. The neutron and proton cross sections of medium-heavy nuclei were evaluated up to 3 GeV for JENDL High Energy Files (JENDL-HE). The nuclei are natural isotopes of K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni and Zn, and total number is 34. The cross section data up to 250 MeV was calculated with the ECIS and GNASH codes. In the energy region from 250 MeV to 3 GeV, the TOTELA and NMTC/JAM codes were used. For neutron incident, the cross section data above 20 MeV is merged into the evaluation of JENDL-3.3. The optical potential parameters of neutron and proton were newly determined by isotopes. The evaluated data were compared with experiment data such as reaction cross section, production cross section and differential cross section. There are acceptable agreements between both. Iron was investigated the double differential cross sections and the leakage energy spectrum by the comparison with benchmark experiments and LA150.

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## [269] Evaluation of Nucleon-induced Cross Sections on Magnesium and Silicon Isotopes up to 3 GeV

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Nucleon-induced cross sections on magnesium isotopes, $^{24,25,26}$Mg, and silicon isotopes, $^{28,29,30}$Si, were evaluated for energies up to 3 GeV. The nucleon scattering cross sections were evaluated by a consistent analysis on nuclear level structure and nucleon scattering data, using a unified framework of soft-rotator model and coupled-channels approach. The scattering cross sections for silicon isotopes were re-analyzed based on two new considerations. First the silicon isotopes were assumed to be deformed nuclei having oblate shapes, second the more sophisticated form of optical potential energy dependence was used. The evaluation of the particle emissions was performed by using a nuclear model code system, GNASH code below 150 MeV and JQMD code above 150 MeV. Comparisons of present results with available experimental data and the LA150 evaluation were made.

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## [293] Possible Fine Structure in the Delayed Neutron Yields in the Resonance Region for Pu-239

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In the previous conference in Tsukuba, the authors proposed a method of analysis of the variation of the delayed neutron yield (DNY) on the basis of multimodal fission model, in which mass and total kinetic energy distributions of fission fragments were represented as a superposition of standard-1 (S1), standard-2 (S2), standard-3 (S3) and superlong (SL) components. The fission yields were calculated with a superposition of Gaussian functions with relevant parameters, considering the proton even-odd effects on the fission yield. The DNYs were calculated with the summation method using different sets of the DN emission probability data.

Hambsch et al. (1989, 2002) found that there were fluctuations in the branching rations to different fission modes at resonances for U-235 and Pu-239. These data, combined with the method mentioned above, resulted in fluctuations in the DN precursor yields in the resonance region; this inevitably led to fluctuations in DNY. In the 2002 paper by Hambsch et al. on Pu-239, however, the mass yield difference from the thermal value for each resonance was not obtained, due to experimental difficulty and insufficient statistics; only the mass yield difference summed over $1^+$-resonances was found to show a definite structure.

Recently they succeeded in deducing the fission mode branching ratios for each resonance. This made it possible to perform analysis for each resonance separately. The result showed that, for most of $1^+$-resonances, the S2 component increases while S1 component decreases; this resulted in local increase in DNY at the resonances, due to contribution of precursors lying near the mass peak of S2-mode. In contrast, for a few resonances, the opposite tendency was observed, which resulted in local dips in DNY at the resonances.

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## [304] Resonance Analysis in the Region of Unresolved Resonances

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A statistical modeling of the resonant cross section structure in the unresolved resonance region has been proposed earlier by introducing the characteristic function of R-matrix elements distribution and

a presentation of this by a ladder of fixed "resonances". The method of the characteristic function has been developed by using the Reich-Moore formalism for the case of non-fissile nuclei under the threshold for inelastic scattering.

An arbitrary cross section functional X can be considered as depending on K-function (K-matrix is determined in the level-matrix form of the collision matrix). The resonance averaging of X is performed by its presentation as a Laplace transform of corresponding original including the characteristic function of joint distribution density of the real and imaginary parts of K. The K-function is formed by using a hypothetical resonant cross sections structure in the energy averaging interval with a set of fixed N resonances.

In applications a resonance ladder with limited number for K-levels is used. This resonance structure's model is assumed with a periodicity to account for the contribution of K-levels that are outside the averaging interval. The parameters of model's ladder are determined by fitting the corresponding characteristic function to the statistical one for the wide variety of nuclei. The resonance averaged cross sections, their moments, average transmission and self-indication functions at arbitrary thickness n, are calculated by using this "resonances" ladder like it is in the resolved resonance region. These calculations are performed by the code HARFOR. An example is presented for calculation of resonance averaged cross sectional functionals.

The further development of the procedure for calculation of resonance averaged cross sections, transmission and self-indication functions is performed by including the inelastic scattering. The results of analysis of resonance neutron capture cross section energy structure near the first threshold of inelastic scattering are reported.

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## [309] SAMQUA - A Program for Generating All Possible Combinations of Quantum Numbers Leading to the Same Compound Nucleus State in the Framework of the R-Matrix Code SAMMY.

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This paper reports the results of a collaborative effort between CEA of France and the DOE of the United States (in particular between le Laboratoire d'Etudes de Physique de Cadarache and the Nuclear Data and Information Analysis Group at Oak Ridge National Laboratory): In preparing input for analyses of differential nuclear data using multilevel multi-channel R-matrix theory, a sometimes daunting and often error-prone task is the generation of quantum-number information for all channels for each compound nuclear state (i.e., for each "spin group", defined by quantum numbers $J^{\pi}$). For many years, the code SAMQUA has been available to users of the R-matrix code SAMMY to assist in preparation of that input; the original SAMQUA code, however, was limited to single-channel spin group information. In this paper, an improved version of the SAMQUA code is described. The new SAMQUA permits inclusion of all open reaction channels in the low-energy interaction between one particle (neutron or charged particle) and a nuclear target, and considerably simplifies the determination of the quantum numbers needed for the definition of the reaction channels. SAMQUA, in addition to its primary function of preparing quantum numbers for the SAMMY input file, also provides the possibility to visualize immediately all open reaction channels. This paper gives also several examples of the use of SAMQUA, with emphasis on the notions of reaction channels and penetrability.

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## [314] Experimental Cross Section Data Base Selection by a SAMMY Reich-Moore Parameterisation of the Resolved Resonant Range: the Case of the $^{9}$Be($\alpha$,n) Cross Section up to 6 MeV.

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The $^{9}$Be($\alpha$,n)$^{12}$C reaction has been of importance as a source of accelerator- or $\alpha$-decay produced neutrons and is still of importance for other applications like astrophysics (neutron production reactions in stars), reactor start-up or diagnostics. Experimental campaigns have been performed periodically on this

reaction, essentially in the sixties, the seventies and more recently in the nineties. The corresponding database is one of the most exhaustive among the ($\alpha$,n) reactions on light nuclei but still contains conflicting data sets, sometimes by more than a factor of two.

In order to clarify the experimental situation and to produce a complete evaluation of the reaction (up to 6 MeV), a Reich-Moore parameterisation of the data has been performed by using the latest version of the SAMMY code which now handles input-output charged-particles data, with the kind assistance of N. Larson, ORNL. From the information available in the literature and from a large variety of experimental data sets (integrated and angular $^{9}$Be($\alpha$,n)$^{12}$C cross sections, neutron total cross sections on $^{12}$C, elastic scattering of $\alpha$ particles on $^{9}$Be), a full consistent Reich-Moore parameter data set has been generated up to 6 MeV for the first time. This paper describes the successive steps involved and the difficulties met during this work.

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## [330] New nuclear data evaluations for Ca, Sc, Fe, Ge, Pb, and Bi isotopes

Arjan J. Koning, Marieke C. Duijvestijn, Steven C. van der Marck, Robin Klein Meulekamp, Alfred Hogenbirk

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New ENDF-6 formatted nuclear data evaluations are presented for all isotopes of Ca, Sc, Fe, Ge, Pb and Bi. Apart from the resonance range, which we have adopted from the best available existing library, the nuclear data evaluations are completely revised, and extend up to 200 MeV. This collection of isotopic evaluations is created by running the nuclear model code TALYS with input parameters that deviate only slightly, or not at all, from the default values, depending on the availablity of experimental data. The isotopic evaluations are thus of comparable quality. For each isotope, the same set of nuclear models is used and, equally important, the same set of ENDF-6 formatting procedures. We have intended to make these evaluations complete in their description of reaction channels, and use a compact method to store the data, which include cross sections, angular distributions, double-differential spectra, discrete and continuum photon production cross sections, and residual production (activation) cross sections including isomers. We have validated the new evaluations with criticality and shielding benchmarks, where available. The data files will be proposed for inclusion in JEFF-3.1.

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## [19] The OECD Nuclear Energy Agency Request List for Nuclear Data

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A high priority request list (HPRL) for nuclear data was established in 1995 by the OECD Nuclear Energy Agency (NEA) Working Party for International Nuclear Data Evaluation Cooperation (WPEC). The HPRL is made public on the NEA Data Bank's Internet pages. At the WPEC meeting in May 2003, it was decided that the list needed to be revised and better maintained in order to improve its value to the nuclear science community. An ad-hoc group, comprising the co-authors of this paper, met in Paris on 9–10 October 2003 to address problems and issues related to the HPRL project. It was concluded that new and more proactive procedures for updating and maintaining the list would be needed to make it more attractive and beneficial to the data user and data producer communities. In addition, it was noted that the existing list was not exclusively composed of high priority requests. It was therefore proposed to establish two lists: one list for general requests of lesser importance or urgency and one list addressing a much smaller number of truly high priority needs, for which the criteria for inclusion and retention would be more rigorous. For example, a high priority request would need to be supported by a quantitative demonstration of the impact and urgency of the request. This paper discusses these recent changes to the NEA data request list project and outlines progress made since the October 2003 meeting in implementing the new procedures.

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## [20] A New Semiempirical Approach of Excitation Functions for (n, p) and (n,$\alpha$) Reactions Based on Evaporation and Exciton Models

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The precise (n, p) and (n,$\alpha$) reaction cross sections are of prime importance from the viewpoint of nuclear applications and fundamental problems of nuclear physics, such as the nuclear transmutation rate, nuclear heating, and radiation damage due to the hydrogen and alpha gas production in the potential first wall structural materials of the fusion-reactor, fast neutron reactor and the sub-critical reactor of an accelerator driven system. However, the available measured data of excitation functions for (n, p) and (n,$\alpha$) reactions are scare and the existing data are scattered about. Thus it is necessary to develop formulae to evaluate the (n, p) cross section of nuclides for which the absence measured data are available. Many parameters such as the binding energy, level density, giant dipole resonance parameters, gamma-branching, the neutron optical potential etc., of the target and residual nuclei, should be input and adjusted in the theory model codes to fit all the measured data. Several systematic studies were proposed to describe the cross section for (n, p) and (n,$\alpha$) reactions. However, those work are not only around the neutron energy of about 14 MeV, but also they are almost based only on the evaporation model, and almost all these work show deviation between the calculation results and measured data. Under the assumptions that the main competing process with proton emission is neutron emission, and the second particle emission is neglected; the preequilibrium emission in the first step in the equilibrium process, which is characterized by exciton n = 3 is only considered , and "never come back", a semiempirical approach to study the excitation functions for the (n, p) and (n,$\alpha$) reactions on the basis of evaporation and exciton models is obtained, and the "pick-up" mechanism of alpha in pre-equilibrium emission is adopted for studying (n,$\alpha$) reaction. In the incident neutron energy range up to 20 MeV and the mass region of 23 A 209, the adjustable parameter of the semiempirical method was investigated. Its strong dependence on (N-Z+1)/A and the incident neutron energy is observed. The for (n, p) reaction resulting from the fit to the 161 experimental data and = 3.222 for (n,$\alpha$) reaction fitting to the 120 experimental data points with four parameters is the lowest of all the existing formulas at En = 14.5 MeV. The predictions of the excitation functions for the (n, p) and (n,$\alpha$) reactions are good agreement with the experimental data. The ratios of the experimental cross sections to systematics calculations are in the region of 0.7 1.3 for (n, p) reaction and 0.6$\sim$1.5 for (n,$\alpha$) reaction in the present work at

neutron energy of 14.5 MeV, and the ratios of M Belgaid's systematic results are during the region of 0.5∼2.0 for (n, p) reaction and 0.5∼1.7 for (n,$\alpha$) reaction 0.5∼2.0 for (n,$\alpha$) reaction These systematic results demonstrate that the contribution of preequilibrium emission must be taken into account in the formulas. Our calculation shows that for medium weight nuclei the fraction of preequilibrium is ∼30 to 50% at En = 20 MeV.

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## [21] MSDM Benchmarks from Proton-Induced Reactions on $^{208}$Pb at Energy of 1 GeV for the Primary Isotopic Yields

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Isotopic production data of proton-induced reactions with the energy ranges up to GeV are of great importance for understanding the reaction mechanisms of intermediate nuclear reactions. Recently, the precise and voluminous measurements of elements produced from proton-induced spallation reactions with energy ranges from MeV to GeV using several target materials have been carried out due to the interest for spallation neutron source and ADS. These experiments show the isotopic cross section of heavy residuals, and the light residuals are not given. The heavy residual production cross section relied on mass spectrometry and radiochemical methods, which only give the cumulative yields due to long-lived residuals resulting from the short-lived beta decay of the primary reaction products. The development of precise spallation reaction models suffered due to the lack of primary experimental data. It is difficult to systematically compare model calculations with available measured data in order to investigate the physical reasons for the shortcomings of the theoretical models. When T Enqvist at GSI used inverse kinematics by bombarding a liquid-hydrogen target with relativistic heavy ions, the cross sections of the all produced primary residuals from manganese to lead were obtained. In the present work, the Many Stage Dynamical Model (MSDM) developed by Russian scientists is adapted to investigate the primary isotopic product cross section of proton-induced spallation on $^{208}$Pb with the energy of 1 GeV. The mass and charge distribution simulations of MSDM with the Fermi-gas level density are 50% larger than the experimental data at the fission peak, lower at spallation part, and two times larger at the region of $50 \leq Z \leq 70$ and $120 \leq A \leq 160$, with the level density of Ignatyuk formula are in good agreement with the experimental data. The primary isotopic production cross sections of fragmentation products from the proton-induced spallation reaction on $^{208}$Pb, with proton energy of 1 GeV for elements from manganese to lead are shown, the MSDM calculation results are in good agreement with experimental data. However, the simulations of MSDM code are lower than experimental data for the elements at the side of neutron-rich nuclides from krypton to antimony. The comparison of the MSDM simulations for the spallation products with Z>65 and A>160 with the measured data is the best, the agreement is shown at the fission fragment with Z<50 and A<120, at the period of $50 \leq Z \leq 65$ and $120 \leq A \leq 160$, the deviations are shown clearly, the reason is due to the statistical error of the Monte-Carlo calculations.

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## [22] Measurements of leakage neutron spectra from thick spherical shells of vanadium and lead with 14 MeV neutrons and validation of their nuclear data

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The leakage neutron spectra from spheres of vanadium and lead with T(d,n) neutron source at their center have been measured by the time-of-flight method from 100 keV up to 14 MeV. The wall thicknesses of vanadium and lead spheres were 155 mm and 227 mm, respectively. The experiment was performed

at the pulsed neutron generator KG-03 of IPPE [1]. The neutrons leaking from the outer surface of a spherical samples were detected with a scintillation counter composed of a paraterphenyl crystal of 5 cm in diameter and 5 cm long and FEU-143 photomultiplier tube. The detector was located at 6.8 m flight path from center of the sphere and was installed in lead house behind a 1 m thick concrete wall. For monitoring of the neutron source yield the alpha-particles produced in the T(d,n)He reaction were detected by a silicon surface barrier detector. The measured data were compared with the MCNP-4 code calculations with nuclear data libraries processed from ENDF/B-6, BROND-2m, EFF-3, FENDL-2. The results of comparison by the spectrum shape and the calculation/experiment values in nine energy groups are presented and discussed.

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## [30] PERFORMANCES OF A 3D MONTE-CARLO CALCULATION ROUTE IN THE CASE OF COMPLEX SYSTEMS (WHOLE SLAB REACTOR CORES) - APPLICATION TO NUCLEAR DATA VALIDATION

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Within the framework of the numerical validation of french neutronic codes (APOLLO2 /CRONOS2), Monte-Carlo calculations play the central role of reference and allow the analysis of model deterministic assumptions to propose new developments. Nevertheless those calculations are usually performed by considering simplified geometries (1D or 2D lattices) and cross-sections (i.e. multigroup) description to save computation time and reduce the statistical accuracy. This involves intricated transposition problems of results to the real (as-built) core configuration. This paper presents whole core calculations (based on JEFF, ENDF/B and JENDL datafiles) in the case of 3D complex systems (32 PWR assemblies made of several kind of heterogeneous UO2 plates).

By using an appropriate GUI (Genuine User Interface) pre-processing software and the French polycinetic transport Monte-Carlo code TRIPOLI4 it is shown that satisfactory accurate results (same standard deviation than experimental measurements accuracy) can be obtained for both keff (around 10pcm, 1sigma) and local power distribution (less than 2 %, 1sigma) calculations. For each kind of calculation the statistical convergence has been studied and a maximum of 24 parallelized CPUs used.

The paper underlines the ability of the calculation route (GUI and TRIPOLI4 code) to investigate both deterministic model biases (self-shielding effects are identified by comparing multigroup and polycinetic TRIPOLI4 calculations) and nuclear data coming from different international sources (JEF2.2/JEFF3/ENDFB6.4/JENDL3.2 nuclear data libraries results compared to integral measurements). The dedicated GUI pre-processing software is used to describe the 3D PWR benchmarks (0.5 million of elementary volumes are need to represent the whole core) and calculations are performed with TRIPOLI4. By comparison with the integral core measurements it is shown that calculated Gd and Hf reactivity worths are systematically overestimated (by 5% to 9%) using both international datafiles. In particular, these results are consistent with previous Hf (reactivity worths) Monte-Carlo calculations performed in the case of simplified benchmarks (which gave rise to new JEFF3 recommended data for the first high resonances of $^{177}$Hf isotope). Furthermore the analysis of $^{235}$U nuclear data (crossed comparisons of evaluated files) stressed the sensitivity of the benchmarks reactivity to capture cross-sections in the epithermal range and a systematic under-prediction (by 600 pcm) with the last JEFF3.0 european file.

Using the same calculation route, biases of assembly and core deterministic models are also quantified and separated. In particular, although the assembly reactivity worths may exceed 500 pcm, it is highlighted that counterbalancing self-shielding effects between the poisoned (Hf and Gd) and standard UO2 assemblies, give rise to small differences between the deterministic (APOLLO2/CRONOS2) and probabilistic calculation routes (less than 100 pcm).

The development of an advanced Monte-Carlo calculation route is under way to cover a wide range of reactor applications (PWR and all the French experimental facility including the new Material Testing Reactor RJH) and help deterministic code users for error analysis. In particular, the same GUI software could be advantageously adapted to the validation of depletion calculations (by an iterative process which consists in getting for each step the cross-sections and performing Monte-Carlo flux calculation).

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## [50] Evaluation of the Fast Neutron Cross Sections of $^{46,47,48,49,50}$Ti including complete covariance information

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A new evaluation of all important neutron cross sections of the stable isotopes of Ti was performed in the neutron energy range 0.212 - 20 MeV, that is the whole energy range above the resonance region. The evaluation combines the results of nuclear model calculations and the complete existing experimental data base in order to obtain the most accurate description of the cross sections present within our present knowledge. Results of recent nuclear model calculations and their estimated covariances are used as prior information for all cross sections except sigma-tot. These priors are successively improved by adding experimental data and applying Bayes theorem to obtain the posterior information using the code GLUCS03. The evaluation of the total cross sections is completely based on the accurate experimental data base for Ti-nat covering the whole energy range of the evaluation. This was done also by means of the code GLUCS03 using an uninformative prior. The results of the evaluation, files 3 (cross sections) and 33 (cross section covariances) for all stable isotopes of Ti will be part of new isotopic evaluations for Ti for the Joint European Fission and Fusion (JEFF) file.

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## [63] Evaluating the dependence of isomeric ratios on some parameters of nuclear reactions

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The dependence of isomeric ratios of nuclear reactions on some parameters such as on the incident particle energy and/or the difference of mass number (A) of the target nuclear and of the product nuclear,...are evaluated via the data from many experiment published. In addition, the experimental isomeric cross section ratios of $^{47}$Ti($\gamma$,p2n)$^{44}$Sc and Y($\gamma$,xn) reactions at the bremsstrahlung end-point energy of 65 MeV at Pohang Accelerator (Korea) are presented and are compared with those obtained by a statistical model calculation.

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## [81] Nuclear Reaction Data Centre Network: A Success Story

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For more than 30 years a world-wide network of nuclear reaction data centres, coordinated by the International Atomic Energy Agency (IAEA), has provided data services to the scientific community. This network evolved in several ways, initially addressing the data needs of the fission reactor industry, and then widening efforts to encompass all types of nuclear reaction data, including neutron-induced, charged-particle-induced, and photonuclear data, and considering the requirements of many other applications such as accelerator driven systems, fusion reactors, nuclear medicine, materials analysis, environmental monitoring, and basic research. Consequently, the four original neutron data centres (i.e., core centers: US National Nuclear Data Center (NNDC), Nuclear Energy Agency Data Bank (NEADB), IAEA Nuclear Data Section (NDS), and the Russia Nuclear Data Center (CJD)) have been joined by nine additional specialized data centers based on particular data types or geographic regions.

Data dissemination methods have developed from mainframe printouts and magnetic tapes through Telnet-based online systems to the World Wide Web (WWW) as the primary media for data distribution. Second-generation WWW retrieval interfaces have been introduced, based on modern database technologies, to provide users with more sophisticated search options, a user-friendly retrieval interface, and additional output options such as improved data plotting capabilities.

A central activity of the network is the collection and compilation of experimental nuclear reaction data and the related bibliographic information in the databases EXFOR and CINDA. The data centres

also distribute all types of nuclear data information, including evaluated data libraries, nuclear structure and decay data, and nuclear data reports. Some of the centres support other means of data distribution beyond their WWW service, including databases on CD-ROM, running mirror web servers, and the creation of small local nuclear data centres. Other nuclear data-related activities specific to individual centers are reviewed, such as the production of nuclear data handbooks and the creation of new databases for special applications through Coordinated Research Projects.

While the initial function of the NRDC network was to ensure data exchange between East and West, the network today ensures the world-wide transfer of information, coordinated sharing of the workload in times of scarce resources, and the evolution of an important repository of nuclear data for future generations.

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## [87] NADS – Nuclear and Atomic Data Systems

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We have developed NADS (Nuclear and Atomic Data Systems), a web-based interface for viewing pointwise and grouped cross-sections and distributions. Our implementation is a client/server model. The client is a java applet that displays the graphical interface, which controls the interactive 2-D, 3-D, and 4-D plots and tables, while the server is a process with data tables in RAM for enhanced access speeds. The server, which manipulates and serves the data, has been implemented in Python using the FUDGE package developed by Bret Beck at LLNL. Computational capabilities include algebraic manipulation and thermal heating of data by users. Many different evaluations are available including Livermore's ENDL-99 nuclear database, ENDF/B-V and ENDF/B-VI. Processed data tables used in Livermore transport codes are accessible as well. NADS is available from http://nuclear.llnl.gov/.

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## [89] Nuclear Data for Waste Transmutation in the EURATOM Fifth and Sixth Framework Programmes

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The Fifth Framework Programme (FP5) (1998-2002) of the European Atomic Energy Community (EURATOM) has come to an end and the Sixth Framework Programme (FP6) (2002-2006) has now started. The Euratom FP6 Research and Training Programme on Nuclear Energy includes three thematic priorities, fusion energy research, management of radioactive waste and radiation protection. It also includes other activities in the field of nuclear technologies and safety. The research on nuclear cross section data for transmutation lies within the topic of Partitioning and Transmutation (P&T) which falls under the thematic priority area of management of radioactive waste. The budget for P&T during the FP6 is about 20% of the overall budget of 190 MEuro for Nuclear Fission and Radiation protection.

For the design of an Accelerator Driven Sub-critical System (ADS), nuclear cross section data are required at high energy for the spallation target and structural materials, and over a wide energy range for the isotopes considered for transmutation. In FP5, the EU has funded two projects on nuclear data. The first project (HINDAS, budget 2.1 MEuro) has been completed at the end of November 2003 and its main objectives were to collect most of the nuclear data necessary for ADS applications such as for the engineering design of ADS, spallation target and structural materials. This has been achieved by basic cross section measurements at different European facilities, nuclear model simulations and data evaluations in the 20-200 MeV energy region and beyond for iron, lead and uranium. The second project (n-TOF-ND-ADS, budget 2.4 MEuro) will be completed at the end of 2004 and it aims at the production, evaluation and dissemination of neutron cross sections for most of the radioisotopes (actinides and long-lived fission products) considered for transmutation in the energy range from 1 eV up to 250 MeV. Measurements are carried out at the n_TOF facility at CERN, Switzerland, at the GELINA facility in Geel, Belgium and using other neutron sources located at different EU laboratories. Further well-focussed nuclear data activities are foreseen in FP6 within the framework of a single large integrated project on transmutation using ADS which is likely to start at the end of 2004.

In 1992, the European Union, Japan, the USA, Norway and the Republic of Korea as the funding parties have established an International Science and Technology Centre (ISTC) at Moscow. The ISTC finances and monitors science and technology projects to ensure that the Commonwealth of Independent States (CIS) scientists, especially those with expertise in developing weapons of mass destruction, are

offered the opportunity to use their skills in the civilian fields. An improved co-operation between ISTC and FP5 EU funded projects on nuclear data for ADS has been established and will be continued in FP6.

The paper will discuss the EURATOM FP5 and FP6 nuclear data projects and the international collaboration in this field including that with ISTC.

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## [92] DETAILED BURNUP CALCULATIONS FOR TESTING NUCLEAR DATA

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A general method (MCQ) has been developed by introducing a microscopic burn up scheme which uses the Monte Carlo calculated fluxes and microscopic reaction rates of a complex system and a depletion code for burnup calculations, as a basis for solving nuclide material balance equations for each spatial region in which the system is divided.

Continuous Energy dependent cross section libraries and full 3D geometry of the system can be input for the calculations. The resulting predictions for the system at successive burn up time steps are thus based on a calculation route where both geometry and cross sections are accurately represented, without geometry simplifications and with continuous energy data, providing an independent approach for benchmarking other methods and nuclear data of actinides, fission products and other burnable absorbers.

The main advantage of this method over the classical deterministic methods currently used is that MCQ System is a direct 3D method without the limitations and errors introduced on the homogenization of geometry and condensation of energy of deterministic methods.

The Monte Carlo and burn up codes adopted until now are the widely used MCNP and ORIGEN codes, but other codes can be used also. For using this method, there is a need of a well known set of nuclear data for isotopes involved in burnup chains, including burnable poisons, fission products and actinides.

For fixing the data to be included on this set, a study of the present status of nuclear data is performed, as part of the development of MCQ method. This study begin with a review of the available cross section data of isotopes involved in burnup chains for power and research nuclear reactors. The main data needs for burnup calculations are neutron cross sections, decay constants, branching ratios, fission energy and yields.

The present work includes results of selected experimental benchmarks and conclusions about the sensitivity of different sets of cross section data for burnup calculations, using some of the main available evaluated nuclear data files (ENDF-B-VI-Rel.8, JEF-3, JENDL-3.3), on an isotope by isotope basis as much as possible.

The selected experimental burnup benchmarks are reference cases for LWR and HWR reactors, with analysis of isotopic composition as a function of burnup. For LWR's ($H_2O$-moderated uranium oxide lattices) four benchmarks are included: ATM-104 NEA Burnup credit criticality benchmark; YANKEE-ROWE CORE V; H.B.ROBINSON UNIT 2 and TURKEY POINT UNIT 3. For HWR's ($D_2O$-moderated uranium oxide cluster lattices), three benchmarks were selected: NPD-19-rod Fuel Clusters; PICKERING-28-rod Fuel Clusters and BRUCE-37-rod Fuel Clusters. The isotopes with experimental concentration data included on these benchmarks are: Se-79, Sr90, Tc99, Ru106, Sn126, Sb125, I129, Cs133-137, Nd143, 145, Sm149-150, 152, Eu153-155, U234-235, 238, Np237, Pu238-242, Am241-243 and Cm242-248.

Results and analysis of differences between calculated and measured absolute and/or relative concentrations of these isotopes for the 7 benchmarks are included on this work.

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## [97] An evaluation of the $^{232}$Th total and capture cross-section from a combined analysis of transmission and capture measurements at GELINA

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The $^{232}$Th(n,$\gamma$) neutron capture cross-section is of primary importance for different reactor systems, such as HTR and ADS, based on the Thorium - Uranium cycle. An analysis of the nuclear data, reveals

that the status of the $^{232}$Th capture data is far from the requested 2 For the analysis of the data in the resolved resonance region the resonance shape analysis codes REFIT and SAMMY were used. A simultaneous analysis of the capture and transmission measurements at different temperatures results in improved resonance parameters. These resonance parameters are interpreted with statistical models, to derive average resonance parameters. We also derive average resonance parameters for the unresolved resonance region from a combined analysis of average capture, total and self-indication measurements. For this analysis the computer codes HARFOR (recently developed at the INRNE Sofia (BG)) and FITACS (developed by Froehner) were used. Both the resonance parameters in the resolved resonance region and the average capture data in the unresolved resonance region result in an improved evaluation of the cross-section data for $^{232}$Th in the resonance region.

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## [103] SIGACE CODE FOR GENERATING HIGH TEMPERATURE ACE FILES; Validation and Benchmarking

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Monte Carlo code system for Neutron and Photon transport (MCNP[1]) have been extensively used for many years in the field of nuclear engineering and reactor design. The MCNP code package requires the nuclear reaction cross section data in a special formatted file known as the ACE (A Compact ENDF) format. The ACE data library is generated by processing the evaluated nuclear data file in ENDF[2] format using the NJOY[3] code system; usually processed at zero degree Kelvin or at 300K. However, many areas of studies such as ADSS (Accelerator Driven Sub-critical System), Fusion reactor blankets and Fast reactor design require nuclear cross section data at some higher temperature.

A code named SIGACE has been developed as a tool for MCNP users within the scope of a research contract awarded by the Nuclear Data Section of the International Atomic Energy Agency (IAEA) (Ref: 302-F4-IND-11566 B5-IND-29641). A new recipe has been evolved for generating high temperature ACE files. The low temperature ACE file is first converted to ENDF formatted file using ACELST code and then Doppler broadened to any desired higher temperature using SIGMA1[4]. SIGACE processes the ENDF and the ACE file to generate high temperature ACE data file for use with the MCNP code. SIGACE code also has a thinning option for the ACE file.

The SIGACE code and the recipe have been validated and benchmarked using the SEFOR fast reactor benchmark problem (Sodium cooled fast reactor benchmark described in ENDF-202/BNL-19302, 1974 document). The SIGACE generated high temperature nuclear data files were used to calculate the Doppler coefficient for the SEFOR fast reactor benchmark problem. The experimental Doppler coefficient and the computed value show good agreement. The Doppler coefficient of the SEFOR reactor calculated using the NJOY generated ACE files also agree with our SIGACE computed results. The code and the recipe is further validated and benchmarked against the numerical benchmark configuration of selected idealized PWR pin cell configurations with five different fuel enrichments as reported by Mosteller[5] and Rahnema[6]. The SIGACE package is available, free of cost, upon request, from the Nuclear Data Section of the IAEA.

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## [110] Direct Simulation of Thermal Neutron Transport Processes Using Evaluated Nuclear Data Files

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The most advanced information related to the accuracy of calculations is available in files of evaluated nuclear data libraries. The usual practice so far applied is that data processing is followed by the Monte Carlo method application. The main idea of the method proposed by us to directly extract the values required from data files. The method being developed allows to directly utilize the data obtained from libraries and seems to be the most accurate technique. Moreover, the method proposed doesn't introduce additional inaccuracy into the final results.

INCOHERENT INELASTIC SCATTERING

Incoherent inelastic scattering is defined for a moderating molecule or crystal by

$$\frac{d^2\sigma}{d\Omega dE'}(E \to E', \mu, T) = \sum_{n=0}^{NS} \frac{M_n \sigma_{bn}}{4\pi kT} \sqrt{\frac{E'}{E}} e^{-\beta/2} S_n(\alpha, \beta, T),$$

where E is the incident neutron energy, E' is the secondary neutron energy, $\beta$ is the energy transfer, $\beta = (E' - E)/(kT)$, $\alpha$ is the momentum transfer, $\alpha = (E + E' - 2\mu\sqrt{EE'})/(A_0 kT)$. The rest of the terms used here are commonly used terms. That is why they aren't given a detailed description. The function $S(\alpha, \beta, T)$ may be presented in File 7 as a table with various interpolation laws or by analytical function using free gas scattering law or short collision time approximation.

SIMULATING ALGORITHMS OF INCOHERENT INELASTIC SCATTERING

The simulated algorithms for case when $S(\alpha, \beta, T)$ is given as a table of values are presented in [1]. New modifications of these algorithms will be presented in this paper. For the case when $S(\alpha, \beta, T)$ is presented as analytical function using free gas scattering law or short collision time approximation we use the change of variables proposed by J.R. Eriksson for free gas model with variables $p = \sqrt{\frac{\alpha A_0 kT}{E}}$ and $q = \frac{\alpha+\beta}{2\sqrt{\alpha}}$. For simulation of scattering we use Eriksson's algorithm with some modifications. For the short collision time approximation we use the same change of variables and obtain the next results:

$$f(p, q) = pe^{-(Ap^2 + Bpq + cq^2)},$$

where $A = (\frac{T}{T_{eff}(T)} - I)\frac{E}{A_0 kT}$, $B = 2(I - \frac{T}{T_{eff}(T)})\sqrt{\frac{E}{A_0 kT}}$, $C = \frac{T}{T_{eff}(T)}$. In these formulas I=0 if $p < 2$, $q < \frac{p}{2}\sqrt{\frac{E}{A_0 kT}}$ and I=1 if it is not true. Both algorithms allows to directly simulate the incoherent inelastic scattering.

The comparisons of our results with MCNP and MCU results are presented in paper.

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## [126] High spin studies with large arrays in Europe: triaxiality, chiral bands and superdeformation

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The recent results obtained with the EUROBALL and GASP arrays in the A=130 mass region will be reviewed, emphasizing the discovery of excited highly-deformed bands and their decay-out, the discovery of chiral doublet bands in Pr nuclei and of stable triaxial bands in Nd nuclei close to the N=82 shell closure, as well as the latest results on superdeformation. The extended studies of the highly-deformed bands in Nd nuclei lead to the observation of the linking transitions over a series of six nuclei, and therefore to the determination of the excitation energy, spin and parity of the states. This also allowed to estimate the neutron pairing strength in the second well from the odd-even mass differences, giving

the first experimental indication that the gap value in the highly-deformed configurations is reduced by a factor of 2 with respect to the value for the normal-deformed ground states [1]. Another topic of interest in A∼130 nuclei in the recent years was the chirality in triaxial rotating nuclei predicted theoretically by Frauendorf [2]. This brought the odd-odd Pr nuclei and their neighbours into the focus of experimental studies in various laboratories around the world, with one of the best examples being $^{134}$Pr [3]. The status of the search of chiral bands at high spins in odd-even and even-even nuclei will be discussed. Very recently, exciting results were obtained from the study of the highest spin states in nuclei close to the N=82 shell closure: the observation of stable triaxiality up to the highest observed spins in $^{138}$Nd, $^{139}$Nd [4] and the observation of the superdeformation in $^{140}$Nd [5]. These achievements lead to the understanding of the evolution of the superdeformation phenomenon along the periodic table, establishing for the first time a "bridge" between two islands of superdeformation, the A=130 and A=150 mass regions. Finally, the new experimental facilities for gamma spectroscopy in Europe (CLARA+PRISMA at LNL and RISING at GSI) will be presented, together with the experiments that are intended to be performed in the near future.

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## [135] Long lived isomeric species around N = 152 deformed shell gap.

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In an early survey of long-lived (t >1 sec) isomers in deformed nuclei, Sood and Sheline [1] found that such isomers are rarely seen in odd-mass actinides, whereas they are quite frequent in odd-odd heavy nuclei, with no isomeric transition (IT) observed in many cases. This latter feature makes the relative energy placement of isomer uncertain. This problem was addressed in a number of detailed structure studies [2-4]. These continuing investigations use the observed Nilsson single particle energies from odd-A neighbours [5] as input data into a realistic modeling of odd-odd spectra[2]. Our recent analysis of 250 Md level structures [6] revealed several interesting features and also provided pointers that led to the present study. An examination of the single particle level spacings in the region [5] shows large gaps at neutron numbers 150 and 152, and corresponding proton gaps at Z = 92, 96 and 100. With the observed neutron orbital spins 7/2 and 9/2 for N = 149 and N = 151 isomers respectively, and the corresponding proton spin being 5/2 or above in most of the cases, we expect isomer pairs with change in angular momentum of 5 units or more, and hence no observable IT, in almost all the odd-odd transuranic nuclei. Presently only 5 such pairs are identified [7] albeit with no unambiguous configurations or relative placement. Using the procedure adopted in our recent 250 Md study [6] we report here the results of our investigations of the 24 expected isomeric species, mostly awaiting identification, in the odd-odd nuclei of this mostly unexplored frontier region.

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## [140] Evaluation of $^{238}$Pu, $^{240}$Pu, $^{242}$Pu decay data

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High-quality and critically evaluated decay data for uranium and transuranium isotopes are needed in order to determine their concentrations in nuclear fuel and related materials, for safeguards, environmental monitoring, radioactive waste management, dosimetry, nuclear medicine and for other applications.

This information was provided by the International Atomic Energy Agency ("Decay Data of the Transactinium Nuclides", Technical Reports Series No. 261, IAEA Vienna, 1986) over 15 years ago. As expected, during this period the number and quality of measurements has dramatically improved, and therefore a re-evaluation is highly desirable and fully warranted.

This evaluation of decay data of three even-even plutonium isotopes takes into account experimental data and other information (compilations, calculations, evaluations) published until 2003. The evaluated values have been obtained using the approaches, programs and procedures adopted by the Decay Data Evaluation Project collaboration.

The following decay data of $^{238}$Pu, $^{240}$Pu, $^{242}$Pu have been evaluated: half-life, decay energy, energy and probability of alpha-transitions, energy and probability of gamma-transitions, internal conversion coefficients of gamma-transitions, energy and relative and absolute emission probability of gamma-rays, energy and absolute emission probability of X-rays, energy and absolute emission probability of electrons.

The evaluated values of the most intensive gamma-ray absolute emission probabilities are the following ones (photons per 100 disintegrations): $^{238}$Pu (43.50 keV) - 0.0397(8), $^{240}$Pu (45.24 keV) - 0.0450(9), $^{242}$Pu (44.92 keV) - 0.0375(8).

The evaluated values of the total U LX-ray absolute emission probabilities (photons per 100 disintegrations) in the decays of $^{238}$Pu, $^{240}$Pu and $^{242}$Pu, respectively: 10.63(8), 10.34(15) and 8.5(4).

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## [143] Parametric studies on fission yields of $^{92}$Sr and $^{140}$Ba for individual peak check measurements in mixed (UOX-MOX) cores.

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In the framework of plutonium recycling in Light Water Reactors, several experimental studies have been launched since 1989 in the French EOLE facility of the French Atomic Energy Commission in Cadarache in collaboration with its industrial partners. One of the main problem to be solved is related to the measurement of the radial fission rates in neighbouring MOX and UOX fuel assemblies. The fission rates are measured by using the gamma-spectrometry technique for each type of fuel (MOX and UOX independently). The measured maps are then normalized together by using a scaling factor involving deduced from a specific measurement by gamma-spectrometry of an individual peak related to well-known fission products ($^{92}$Sr or $^{140}$Ba). The cumulative fission yields in the actual situation are also required to determine this scaling factor : several evaluations of such yields are available in the NEA databank (ENDF-B6, JEF2.2 and JENDL3.2). This paper is dedicated to the analysis of the last experiments, in which a great effort was undertaken to improve the experimental technique ; the first part gives an overview of the experiments and of the experimental technique. The second section is devoted to the parametric study and the last paragraph concludes the paper. The scaling factor is directly linked to the recommended fission yield associated to $^{92}$Sr and $^{140}$Ba, and to the relative fission rate of fissionning isotopes in the considered fuel pins. When we compare the recommended data libraries related to the fission yields, one observes some discrepancies between the yields (for example the yield of $^{140}$Ba related to $^{239}$Pu is 3.8% lower in JEF2.2 file than in ENDF-B6 ; the $^{92}$Sr yield for $^{239}$Pu in JEFF3 is 6.6% higher in JEFF3, etc.). Furthermore, the uncertainties given in the JEF2 file are higher than the ENDF-B6 data, the JENDL3.2 libraries given any uncertainty. The average yield weighted by individual fission rates, is obtained by calculation using either Monte-Carlo or deterministic codes, introducing consequently some additional uncertainties. The analysis of the experiments show discrepancies in the scaling factor obtained with the different recommended libraries. For example, in a UOX/MOX specific configuration of the MISTRAL programme, we obtained f=2.53±1.6% and f=2.48±1.6% for the $^{140}$Ba from ENDF-B6 and JEF2.2 respectively, the JEFF3 evaluation giving f=2.47±4.1%. For the $^{92}$Sr, the results are about in average 10% lower than the $^{140}$Ba solutions and the uncertainties are higher but this spread is not consistent with the experimental margins. The new evaluation JEF3 doesn't improve this. The uncertainty is higher for the JEF2.2 $^{92}$Sr scaling factor than the ENDF-B6 result. For JEF3 data, the uncertainties are consistent between $^{140}$Ba and $^{92}$Sr, but it seems that the $^{140}$Ba is too pessimistic. Same trends can be observed for the EPICURE and the BASALA programmes ; the results will be published in the full paper indicating that the fission yields must be revised.

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## [147] Neutron Data Evaluation and Validation of Rhodium-103

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Rhodium-103 is a prominent fission product for nuclear reactor simulations as well as an usual detector in fast neutron activation or dosimetry techniques. However, the reactions and the energy regions of interest differ significantly depending on the applications. Nevertheless, the evaluated nuclear data should cover all application needs while enforcing physics. In order to ensure its internal consistency, this new evaluation is entirely based on nuclear models.

At low energy (a few eV), the Reich-Moore approximation of the R-Matrix (SAMMY code) was applied to take into account recent GELINA transmission and radiative capture measurements relevant to thermal reactors.

In the unresolved resonance range, average parameters of the Hauser-Feshbach formalism (SAMMY / FITACS code) were adjusted onto experimental data up to the inelastic threshold.

At higher energy, the coupled-channels optical model (ECIS code) was used together with a semi-microscopic deformed potential (SMOM code) to calculate total, reaction and direct inelastic cross-sections as well as transmission coefficients. The latter were eventually employed in statistical models (TALYS code) to split the reaction into all open channels. Every calculated value was tested against differential data when available and compared with other evaluation works.

The quality of the transitions between the above three energy ranges was assessed with the help of statistical techniques to test the resolved resonance parameter distibutions and the SPRT method to check optical model calculation.

The evaluated data has been transformed into the ENDF-6 format (TEFAL code), tested (ENDF utility codes) and finally processed for the end-users (NJOY code). Apart from this minimal verification procedure, the quality of the data was tested against relevant integral results for activation and thermal reactor applications. This new file will be proposed for insertion into the next release of the JEFF-3 General Purpose and Activation libraries.

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## [155] FUDGE: A program for performing nuclear data testing and sensitivity studies

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We have developed a program called FUDGE which allows one to modify data from LLNL's nuclear database. After modification, FUDGE can then be instructed to process the data into the formats used by the deterministic (ndf) and the Monte Carlo (MCAPM) transport codes. This capability allows end users to perform nuclear data sensitivity studies without modification of the user code. FUDGE is designed to be user friendly (object-oriented) and fast (the modification and processing typically takes about a minute). It uses python as a front-end, making it flexible and scriptable. Comparison, plotting and printing of the data are also supported. An overview of FUDGE will be presented as well as examples.

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## [159] Analysis of Deuterium Scattering on $^{6,7}$Li up to 50 MeV based on Realistic Effective NN Interaction

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The double-folding (DF) model [1,2] of the deuterium-nucleus optical potential has been involved within a semi-microscopic analysis of the elastic scattering of deuteron on $^{6,7}$Li for energies up to 50 MeV, of interest for the calculation of the D-Li neutron source term [3]. The direct and exchange real parts of the microscopic real optical potential, including nucleonic and mesonic form factors, are given in

terms of the projectile and target nuclear densities respectively, which are folded with a realistic effective NN interaction [4]. The deuteron density distribution has been obtained from the Machleidt [5] S wave function while for the target nuclei $^{6,7}$Li we have used a gaussian form with parameters obtained from either the analysis of the electron scattering data of Bray et al. [6] for $^{6}$Li, or the shell model calculations by Satchler and Love [1] for $^{7}$Li. The Paris M3Y effective interaction [7] has been chosen for consistency with the deuteron density distribution. Finally, the real DF potential has been applied for description of the deuteron scattering data from 1 to 50 MeV, in conjunction with appropriate Woods-Saxon imaginary and spin-orbit potentials by using the code SCAT2 [8] modified to include the DF potential. No adjustable parameter or normalization constant of the DF real potential was involved in this work. The comparison of the calculated results with the bulk of experimental elastic scattering angular distributions for the $^{6,7}$Li nuclei has provided imaginary surface and spin-orbit potential parameters for the various incident energies. Moreover, their average values have made possible the establishment of energy-dependent phenomenological imaginary and spin-orbit potentials for the interaction of deuterons with the Li isotopes. Altogether the results of this analysis support the concept to reduce the phenomenological part for the potentials to describe deuteron scattering data by the use of microscopic calculations. Further work concerns the adjusting only the real phenomenological potential parameters while the imaginary and spin-orbit components remained unchanged, in order to provide a full average parameter set which can be more easily used in further analyses or still missing predictions of deuteron interaction with $^{6,7}$Li. On the other hand additional experimental data to guide and benchmark the model calculations at incident energies above 15 MeV, where only two measurements exist up to 50 MeV, are strongly requested.

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## [163] Development of High Energy BROND Library up to 150 MeV

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Investigations aimed at the development of neutron cross-section evaluations and creation of High Energy BROND library for actinides in the range up to 150 MeV are discussed. The complete data files for $^{232}$Th, $^{238}$U, $^{239}$Pu, $^{240}$Pu, $^{237}$Np and $^{241}$Am have been created at the IPPE during the last years.

The coupled-channel optical model has been used to calculate the neutron total, elastic, and reaction cross sections and the elastic scattering angular distributions. The parameters of the optical model have been determined on the basis of available experimental data including the recent precise measurements of the total cross sections for $^{232}$Th and $^{238}$U. The calculations based on these parameters describe consistently the available data on neutron and proton absorption cross sections in a wide energy range and enable to evaluate the total and elastic scattering cross sections for actinides with a higher accuracy than previous evaluations. Analysis of data has been performed both below and above 20 MeV neutron energy.

Evaluations of the fission cross sections, the secondary neutron multiplicities and spectra, as well as the charged particle production cross sections are performed in the frame of the statistical model that includes direct, preequilibrium and equilibrium mechanisms of nuclear reactions. For neutron energies above 20 MeV the evaluation of fission cross sections was obtained using statistical optimization with rational functions. Such approach allows us not only to provide the critical selection of experimental data, but also to determine uncertainties of evaluations together with the corresponding covariance matrix. The description of multiplicity and spectra of secondary neutrons was realized separately for the events with and without fission. The Kalbach parameterization of angular distributions has been used to describe

the double-differential cross sections of emitted neutrons and charged particles in ENDF/B-VI format. The recently published experimental data have been used to estimate more precisely model parameters for charged particle production. The direct and pre-equilibrium pick-up and knock-out mechanisms were taken into account for the cluster emission.

The created files are intensively used now for the comparative analysis of developing accelerator-driven systems.

The results obtained were supported partially by the ISTC Project #1372.

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## [181] Systematics of rotational bands in odd-mass nuclei on the basis of the variable moment of inertia model.

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On the ground of a file of the evaluated nuclear data ENSDF the most complete compilation of rotational bands in odd-A nuclei with mass numbers $43 \leq A \leq 253$ is presented. The processing of experimental data is carried out on the basis of generalization of the variable moment of inertia model for axial strong deformed nuclei which is taking into account the decoupling effect for bands with K=1/2. The good description of rotational energies for the majority of rotational bands is obtained and the systematic behavior of the model parameters in all areas of the deformed nuclei is shown. The theoretical description is used for association of fragments of rotational bands, exclusion of "superfluous" levels and prediction of a placement of "missed" levels.

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## [185] Properties of the monopole excited states of even-even nuclei

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New the most complete compilation of data on properties of monopole excited (0+) states of even-even nuclei is presented. The existent theoretical notions about their structure and the properties of E0-transitions are analysed. In the light, closed-shell, spherical, deformed and transitional nuclei the main modes of nuclear motion forming both the lowlying 0+ states and giant monopole resonances are selected. The typical results of calculations obtained within collective and microscopic models as well as qualitative considerations concerning the nature of these states based on the systematics are given. For the description of the E0-transition intensity the single-particle estimate and model-independent sum rule are used. The special attention is paid to the anomalies shown in decay properties of the monopole states and their physical treatment.

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## [189] Energy of the $3/2^+$ state of $^{229}$Th revisited

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The unusually low energy of the $3/2^+$ isomeric state of $^{229}$Th makes this an interesting nucleus to study the interaction between atomic and nuclear degrees of freedom. The adopted excitation energy, $\Delta$=3.5(10) eV, was determined from some assumptions related to the level scheme and gamma-ray transitions in $^{229}$Th and a careful investigation of the gamma-ray energies [1]. Recently, [2,3] two different hypotheses related to the 29 keV, 71 keV, and 146 keV transitions in $^{229}$Th were suggested.

In this work we investigated the consequences of those hypotheses using the experimental information quoted in refs. [1,4], the statistical procedure of ref. [5], and gamma-ray standards from [6]. In a first step we adopted the common hypotheses of refs. [1-3,7] and determine the energies of the three transitions above and of the $^{229}$Th levels.

In a second step we tested the two hypotheses. Supposing that the 146 keV feeds the g.s. and the 29 keV and the 71 keV feed the $3/2^+$ level [2], we obtained $\Delta$=2.3(10) eV with P($\chi^2$)Assuming that the

146 keV feeds the $3/2^+$ level and that both the 29 keV and the 71 keV transitions feed partially the $3/2^+$ level (with relative intensities of 75% and 60%, respectively) and partially the g.s. [3], the result is $\Delta$=5.9(10) eV with P($\chi^2$)=33%.

The assumptions that the 29 keV and 71 keV feed both the $3/2^+$ and the g.s. agree well with the experimental data and affect the adopted value of $\Delta$. Since the interaction between atomic and nuclear degrees of freedom depends strongly on $\Delta$, these assumptions must be carefully investigated.

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## [209] Investigation of Cf-252 fission spectra and SINBAD shielding benchmarks using TRIPOLI-4.3 code and JEFF-3.0 library

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The Cf-252 neutron source is an important reference source for neutron detectors and neutron dosimeters calibration. It is also widely used in integral shielding experiments as a neutron source (1).

There are several evaluations of the Cf-252 spontaneous fission neutron source spectrum. The published Cf-252 source spectra representations include one parameter Maxwellian spectrum and two parameters Watt spectrum. They are described as follows:

I) Maxwellian ISO standard spectrum (T=1.42 MeV) (ISO 8529),
II) NBS Modified Maxwellian spectrum (T=1.42 MeV) (NBSIR-85-3151),
III) Watt spectrum (a=1.025 MeV and b=2.926 $MeV^{-1}$) (LA-13675),
IV) Watt spectrum fit (a=1.175 MeV and b=1.040 $MeV^{-1}$) (2, 3).

Spectra I), III) and IV) can be applied in continuous energy way in Monte Carlo neutron transport calculation and spectrum II) is a multi-group representation including the modified segments. Differences between the shapes of the low energy trail regions of the spectrum are particularly interesting, and the recent benchmark exercise (2, 3) has shown some evidence to suggest that the Cf-252 Watt spectrum fit is a good spectrum to be used.

TRIPOLI-4 continuous-energy Monte Carlo transport code (4), developed at CEA/Saclay, has been extensively applied in radiation shielding, criticality safety, reactor physics and nuclear instrumentation. In this study, TRIPOLI- 4.3 modelling on shielding benchmarks was prepared to evaluate the impact of different evaluations of the Cf-252 source spectrum. Four different benchmarks from SINBAD shielding data base (1), Winfrith water benchmark, NIST neutron leakage from water spheres benchmark, Karlsruhe and Illinois iron sphere benchmark experiments, were investigated.

The calculated results obtained with cross-section libraries ENDF/B-VI.4 and JEFF-3 will be presented for the above-cited Cf-252 fission spectra and shielding benchmarks.

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## [219] Neutron Cross Sections Evaluation with Taking Unrecognized Experimental Uncertainties into Account

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Unrecognized experimental uncertainties are a main source of the underestimation of evaluated cross-section uncertainties [1]. A method for taking unrecognized experimental uncertainties into account in statistical analysis of neutron cross-section measurements is proposed. The method is based on the construction of probability distributions for observable deviations of the the measurements from the model function within energy intervals. A compromise is achieved between a width of the energy intervals and the number of data sets and measurements falling into the intervals. As input information only measured cross-section values (as the data with essentially higher confidence level than declared uncertainties) are used. Special procedure is applied for refining constructed covariance matrices from the unphysical ones. A search of the vector of estimated parameters is carried out in iterative procedure with minimization of statistical functional and re-calculation of the covariances for the observable deviations at each step. As an initial approximation for the model function any of existing evaluations properly parametrized can be used.

A calculational scheme is heavily based on identical transformation of the equations of generalized least squares method [2]. In particular, the transformation permits to decrease a size of matrices to be inverted from the total number of measurements to the number of experimental works.

The method was applied for the evaluation of the (n,t), (n,f) and (n,g) reaction cross-sections on fissile isotopes. It produces reasonable results in cases when generally accepted statistical methods fail. A comparison with the results of calculations carried out with the GMA code [3] for the same experimental data bases is presented.

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## [237] Dynamical collective clusterization in hot and rotating nuclei

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The hot and rotating nuclei, formed in light heavy-ion reactions, decay subsequently by the emission of mainly light-particles (LPs, with A≤4, Z≤2) and a small fraction (5-10%) of complex intermediate mass fragments (IMFs, with 4<A<20, Z>2), also called clusters. In order to understand this phenomenon, a collective clusterization model [1] is developed, which treat both the LPs and IMFs as the dynamical collective mass motion of preformed clusters through the barrier. Interestingly, within the same dynamical model treatment of both LPs and IMFs, without invoking any statistical model considerations, the LPs are shown to have different characteristics as compared to the IMFs. It is for the first time that a non-statistical dynamical description is developed for the emission of LPs from a hot and rotating compound system. The model is worked out in terms of only one parameter, namely the neck-length parameter, which is related to the total kinetic energy TKE(T,$\ell$=0) at temperature T and angular momentum $\ell$=0 of the hot compound nucleus, defined in terms of the binding energy of the hot compound nucleus and the ground-state binding energies of the finally emitted fragments. The systematic variations of the cross-section for the emission of LPs and IMFs, calculated on this, so-called, dynamical cluster-decay model (DCM) is similar to that predicted by the statistical fission models. The model is applied to the decay of $^{116}$Ba$^*$ formed in $^{58}$Ni+$^{58}$Ni reaction at various incident energies. Also, the average $\overline{TKE}$ are calculated.

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## [243] Fast Neutron-induced Fission Yields of $^{232}$Th Measured Using an ISOL System

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We have measured the cumulative yields of fast neutron induced fission of $^{232}$Th, at the ISOL-facility at the Studsvik R2-0 reactor, with the technique developed by Rudstam et al. The fission products measured cover nuclides, as well as their isomers, for the light masses Zn to Sr (Z=30 to 38), and heavy masses from Cd to Ba (Z=48 to 56) respectively, with half-lives from < one second to hours. The yields are corrected for the delay of the fission products in the thorium target and for the ion separator efficiency, and are normalized to published experimental data or yield values calculated using Wahl's semiempirical model, to obtain absolute yields. The delay parameters are determined from yields of $^{235}$U measured in a separate experiment with the same ion source. Few previous experimental fission yield data for $^{232}$Th have existed. Our results add more than 200 new yield data to the nuclear fission data base, which can be used for better understanding and theoretical modeling of fission process.

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## [265] Development of Nuclear Data Processing and Utilization System for Innovative Reactors

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A research and development (R&D) project on an integrated nuclear data utilization system started in 2002 for five-year plan for innovative nuclear energy systems such as innovative reactors and accelerator-driven systems.

The integrated nuclear data utilization system is being developed as a modular code system, which consists of nuclear data search, retrieval and graphic plotting engines, and data processing and utilization system.

The system is planning to use on PC-Linux server through Internet for registered users, so that it has a graphic user interface (GUI) in order to easily utilize the system for various nuclear design studies in the innovative reactor development.

The nuclear data processing and utilization system, which is able to handle JENDL-3.3, ENDF/B-VI and JEFF-3 to generate point-wise and group-wise cross sections in several formats, and has a capability to perform criticality and shielding benchmarks. Verification of nuclear data is available by using various criticality and shielding benchmark problems selected from database such as International Criticality Safety Benchmark Experiments Project (ICSBEP) and Shielding Integral Benchmark Archive and Database (SINBAD). The system performance highly depends on the quality of benchmark problems so that good benchmarks should be selected from existing database. We have determined selection criteria for adoption of benchmark problems.

The nuclear data processing and utilization system was constructed on the concept and the procedure of development. A prototype system was developed to examine the operability of the user interface and discuss detailed specifications of the system. The system is expected as a verification tool of nuclear data for development of innovative nuclear reactors, because cross-section generation with nuclear data and the various benchmarks for criticality and shielding problems can be easily performed. The system is also expected to apply quality assurance program for the next JENDL project.

This work was performed under contract with Ministry of Education, Culture, Sports, Science and Technology (MEXT).

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## [299] Evaluated nuclear data for neutron transport calculations in structural & fissionable materials at energies up to 250 MeV

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Evaluated nuclear data for use in the neutron transport problems have been developed.

The evaluated nuclear data are obtained for structural materials ($^{51}$V, $^{52}$Cr, $^{56}$Fe) at neutron energies up to 250 MeV and fissionable and fissile isotopes: $^{238}$U, $^{239}$Pu at neutron energies up to 50 MeV, $^{240}$Pu and $^{235}$U up to 100 and 300 MeV accordingly.

The evaluated nuclear data files include information on total reaction cross-sections, cross-sections for elastic and inelastic interactions of neutrons with nuclei, fission cross-sections and number of neutrons per fission (for fissionable materials), cross-sections of (n,2n), (n,3n), (n,4n), (n,p), (n,np), (n,2n), (n,$\alpha$), (n,n$\alpha$) reactions and others, threshold reaction cross-sections as well as energy and angular distributions of secondary neutrons, protons and alphas.

Evaluated nuclear data are recorded in ENDF-6 format.

At the energies below 20 MeV the data were adjusted with account of ENDF/B-VI and JENDL-3 data.

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## [305] Validation Analyses of IEAF-2001 Activation Cross-Section Data for SS-316 and F82H Steels Irradiated in a White d-Li Neutron Field

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A complete activation data library, the Intermediate Energy Activation File IEAF-2001 has been recently developed for applications to intermediate energy systems. It contains neutron-induced activation cross sections up to 150 MeV neutron energy for 679 target nuclides from hydrogen to polonium. Two different working libraries with 256 group data stored in different data formats have been derived for application calculations. One of them can be used by activation codes capable of handling an arbitrary number of reaction channels such as ALARA of the University of Madison-Wisconsin. The other one uses pseudo fission product yields to describe the generation of transmutation products and can be used with standard activations codes such as FISPACT of UKAEA Culham.

This paper presents IEAF-2001 validation analyses for SS-316 and F82H steels using results of activation experiments performed previously at the FZK cyclotron. Samples of SS-316 and F82H steels were activated in a white neutron field produced by a 40 MeV deuteron beam on a thick lithium target. The samples were exposed to a neutron fluence of 3 $10^{15}$n/cm$^2$. The gamma-activities of 35 unstable nuclides in SS-316 and 22 in FH-82 were recorded at cooling times between 1 hour and 150 days.

For half of the measured radio-nuclides, the IEAF-2001 calculations agree with the measurements within the experimental uncertainty of typically 10-30%. This includes the main contributors to the total activity and the contact dose rate of the SS-316 and F82H steels, such as $^{56}$Mn, $^{57}$Ni, $^{58}$Co, $^{54}$Mn and $^{60}$Co. For other radio-isotopes the calculation-to-experiment ratios varying between 0.03 and 5 were obtained. In particular this applies for activation reactions with reaction thresholds above 20 MeV such as $^{92}$Mo(n,3na)$^{86}$Zr. It was also found that sequential charge particle reactions significantly contribute to the production of several radio-isotopes.

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## [307] Gamma Spectroscopy and Gamma-ray Intensity determination for $^{48}$V

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The $^{48}$V beta and electron capture decay was studied by gamma-ray spectroscopy. Targets of natural metallic Titanium, 99.99∼% purity, 0.6∼mm thick, were irradiated in the IPEN/CNEN-SP Cyclotron Accelerator with 24∼MeV protons, degraded to 17∼MeV with a thin Al foil, and 2$\mu$A current. The $^{48}$V was obtained by the $^{48}$Ti(p,n) reaction along with $^{44}$Sc, $^{46}$Sc, $^{47}$Sc, $^{48}$Sc concurrent products. It was also observed $^{56}$Co from impurities. The waiting time from the end of the irradiation to the beginning of the gamma-ray measurement was one week to allow for the $^{48}$Sc, 44∼h, decay. The energy and relative efficiency calibrations were performed with a $^{56}$Co source produced in the Cyclotron accelerator through the $^{56}$Fe(p,n) reaction using a natural iron target similar in shape to the Titanium one. The gamma-ray spectroscopy system used a 35% efficiency HPGe detector, 1.85∼keV nominal resolution for 1.33 MeV $^{60}$Co photons. The energies, in keV, and intensities, in photons per parent decay, of the observed gamma-rays are: 802.85(4) - 0.00136(12), 928.34(6) - 0.007871(25), 944.135(12) - 0.07871(5), 983.526(5) - 0.99993(23), 1312.115(5) - 0.98215(14), 1437.529(15) - 0.001196(7), 2240.396(16) - 0.23328(17), 2375.20(4) - 0.000087(4), 2420.93(4) - 0.000067(4), where the uncertainties are given between parentheses in units of the least significant digit. In many cases, these energies and intensities are an order of magnitude more accurate than previously known. Two lines formerly assigned to the $^{48}$V decay, at 938 and 1063 keV, were not observed; their intensities upper limits determined in this experiment were $< 10^{-5}$, and $< 5.10^{-5}$ photons per parent decay, respectively.

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## [339] The role of $^{234}$U transitional levels in the photofission fragment angular distributions.

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The angular distributions of $^{234}$U photofission fragments, are interpreted via calculated transitional levels for E1, M1 and E2 excitation in the first and second saddle points.

The deformation energies and corresponding parameters in the saddle points, were calculated [1] by taking into account the Strutinsky shell corrections [2]. The Pashkevich parametrization [3] has been used to describe the nuclear shape. Single particle spectra for neutrons and protons were calculated using the Woods-Saxon deformed potential, with Chepurnov parameters [4]. The deformation parameters for these saddle points and the single particle levels, were used as input in the calculation of the quasi-particle and rotational spectra, and a more realistic level density calculation was performed using Lipkin-Nogami projectors in the BCS approach [5].

We would like to point out that our approach was previously employed with success in the calculation of the transition nucleus levels at saddle points[6], which allowed the identification , for the first time, of a concentration of M1 strength in the electro- and photofission of $^{239}$Pu near the fission barrier, plus and an explanation for the main experimental structures in $^{237}$Np ($\gamma$,f) cross section[7].

In the present study of $^{234}$U we found strong evidences supporting the occurrence of a degeneracy of the (2+, 0) and (1-, 0) transition levels.

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## [363] Review of Non-neutron and Neutron Nuclear Data, 2004

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Review articles are in preparation for the 2004 edition of the CRC Handbook of Chemistry and Physics dealing with the evaluation of both non-neutron and neutron nuclear data. Data on the discovery of element 110, darmstadtium, and element 111 have been officially accepted, while the data on element 118 have been withdrawn.

Data to be presented include revised values for very short-lived nuclides, long-lived nuclides and beta-beta decay measurements for quasi-stable nuclides. There has been a re-assessment of the spontaneous fission (sf) half-lives which distinguishes between sf decay half-lives and cluster decay half-lives and with cluster-fission decay.

New measurements of isotopic abundance values for many elements will be discussed with an emphasis on the minor isotopes of interest for use in neutron activation analysis measurements.

Neutron resonance integrals will be discussed emphasizing the differences between the calculated values obtained from the analytical integration over neutron resonances and the measured values in a nuclear reactor-spectrum, which does not quite conform to the assumed 1/E neutron energy spectrum. The method used to determine the neutron resonance integral from measurement using neutron activation analysis will be discussed.

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## [367] Measurement and analysis of neutron and photon flux spectra inside a Tungsten block irradiated with 14 MeV neutrons

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Tungsten is a preferred structural material in fusion devices because of its excellent thermal properties and reduced activation characteristic. As part of the European Fusion Technology Programme a benchmark experiment was carried out in collaboration of TU Dresden with ENEA Frascati and FZ Karlsruhe to test the reliability of nuclear data files for Tungsten. A W block with front area of 47cm x 47cm and 49cm length was irradiated with 14 MeV neutrons at the Frascati neutron generator (FNG), and the induced neutron and photon flux spectra were measured central inside the block at distances of 5, 15, 25, 35 cm from the front area. Both neutron and photon flux spectra were simultaneously measured using the TUD NE-213 pulse height spectrometer. The spectra unfolding was done with the DIFBAS code on base of absolute detector responce matrizes. MCNP-4C calculations with different nuclear data libraries, here the Fusion Evaluated Nuclear Data Libraries FENDL-1, FENDL/MC-2.0 and the European Fusion File EFF-2.4 were tested against the experimental results to proof the accuracy of the used nuclear data. In Monte Carlo calculations a full 3D geometry model of the assembly was taken. The spectra were calculated as average flux in the volume element considered by means of the track length estimator of MCNP. The comparison between experiment and calculations is made in full detail between 1 and 15 MeV for neutrons and between 0.4 and 9 MeV for photons and also in C/E-ratios (calculation/experiment)of significant fluence integrals. In tendency the C/E-ratio decrease for the neutron fluences with increasind depth of the measuring position. Starting from C/E=1 for z= 5cm, the neutron fluence measured is well reproduced within 20

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## [378] Actinide cross section evaluations

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The Livermore Computational Nuclear Physics group is charged with producing updated evaluations for all the actinides in the coming year, concentrating on fission, capture and (n,2n) cross sections. We attack this daunting task either by adopting other recent evaluations or by performing our own. Owing to the large number of nuclei involved, we seek to automate the evaluation process as much as possible. For this purpose, we have developed a fitting code that takes all relavant EXFOR data for a reaction or set of reactions and performs a generalized least square fit to them, subject to various constraints and other prior information. The constraints include such things as threshold constriants and sum rule contraints. Other prior information includes information gleaned from systematics and other model calculations. We compare our results to some other recent evaluations in this mass region.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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## [392] Verification of neutron-gamma calculations by means of TLD-measurements in iron, water and air

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Considering the new interest in gamma fluence spectra due to possible gamma radiation damage of pressure vessels, new neutron-gamma experiments have been realized. As complement to spectrum measurements with NE-213 and high-purity Ge detectors, absolute integral meaurements with different types of Li:Mg,Ti thermoluminescence dosimeters (TLD) were performed at the experimental channel of the Zittau Training and Research Reactor at different depths of water, iron and air layers. Due to small dimensions of the TLDs, these measurements allowed a much better spatial resolution and smaller perturbations of the measured gamma and neutron radiation field than the spectrum measurements. To check available codes and nuclear data, Monte Carlo calculations were obtained for the measurement points with different nuclear data files and compared with the measured TLD-responses. The reasons of discrepancies are discussed.

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## [395] Comparative Study of Safety Related Core Parameters for a LEU and Mixed Fuel Core of a Swimming Pool Type Research Reactor

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Pakistan Research Reactor PARR-1 is a swimming pool type research reactor utilizing, Low Enriched Uranium (LEU) fuel and operating safely at thermal power of 10 MW. It has been planned to operate the reactor with the mixed LEU and HEU (Highly Enriched Uranium) fuels. To evaluate the performance of the mixed fuel core in comparison with the presently operating LEU core from safety point of view, calculations have been performed for safety parameters of both the cores. The calculated parameters include average power density in the fuel region, power peaking factors, power density profile in the hottest channel and reactivity feed back coefficients related with variation in fuel temperature, moderator temperature and moderator density. Cross sections generation lattice cell code WIMS-D/4 and core analysis code CITATION have been employed for this purpose. For these calculations, burnup dependent cross sections data has been generated for LEU and HEU fuels at normal operating core conditions as well as at various fuel and moderator temperatures, and moderator densities.

The comparison of calculated results for PARR-1 mixed fuel core with that operating LEU core reveals that; i) the average power density in fuel region for mixed core is slightly higher, ii) the total power peaking factor for mixed fuel core is about 5% less , iii) average value of fuel temperature coefficients for mixed

core is about 15% smaller iv) no significant difference is found in the values of moderator temperature coefficients for both the cores, and v) moderator density coefficients for mixed core are less by about 6%. Though lower values of fuel temperature and moderator density coefficients for mixed core apparently indicate lower safety margins for this core. However, detailed transient safety analysis of mixed core based on these results have proved that overall impact of all the above mentioned safety parameters for mixed fuel core do not differ significantly from that of LEU core. Therefore, PARR-1 can be operated safely with mixed fuel.

**Keywords:** PARR-1, LEU Fuel, Mixed Fuel, Safety Parameters, WIMS-D/4, CITATION, Nuclear Cross-sections Data.

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## [399] The NEA Working Party on International Nuclear Data Evaluation Cooperation - Recent achievements and future plans

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The OECD Nuclear Energy Agency (NEA) Working Party on International Nuclear Data Evaluation Cooperation is an international collaboration between the evaluation projects in Japan (JENDL), United States (ENDF), and Western Europe (JEFF). The participation of the evaluation projects in non-OECD Member countries (BROND, CENDL, and FENDL) is supported by the International Atomic Energy Agency (IAEA).

The Working Party has completed and published a number of co-operative studies aiming at improving the accuracy of the evaluated nuclear data, used in most applied nuclear calculations. The latest studies concerned delayed neutron data for the major actinides, fission neutron spectra of Uranium-235. The Working Party has also on-going studies on nuclear data standards, activation cross-sections, evaluation and processing of covariance data in the resonance region, neutron cross-sections for the bulk of fission products, and nuclear data for improved LWR reactivity predictions.

The Working Party is also sponsoring three long-term collaborative studies dealing with:

- The development of modern nuclear model codes,
- Evaluated nuclear data format and processing problems,
- The high priority request list for nuclear data

The outcome of these studies will be reflected in all major evaluated data files and will help to eliminate the outstanding discrepancies in these files.

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## [436] Testing of recent JEF(F) decay data and fission product yields files for irradiated nuclear fuel decay heat calculations.

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The heat generated by irradiated nuclear fuel is one of the important considerations for its safe storage, transport and possible recycling.

One method to calculate the decay heat of irradiated fuel is from an inventory code such as FISPIN [1] or ORIGEN-S [2]. These codes were part of a code comparison that showed that their results, and that of many other codes, were dependent upon the nuclear data used by the code rather than the solution method [3].

This paper compares FISPIN10 decay heat calculations with a selection of fission pulse experiments (U235, U238, Pu239 and Pu241) [4-7] and PWR UOX assembly calorimetry measurements [8]. FISPIN10

can be run with a selection of ENDF/B formatted decay and fission yield files from the JEFF project. Currently libraries include JEF-1 (1986) [9] and JEF-2.2 (1993) [10]. This work also considers a new UK fission product yield file and preliminary decay data file that is being considered for release in the JEFF-3 file.

This work was partially funded by the UK Industry Management Committee.

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## [438] Electric Monopole Transitions between $0^+$ States for Nuclei Throughout the Periodic Table

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The fact that electric monopole (E0) transitions between states of the same spin and parity are possible in a nucleus enclosed by electrons is well known. The electric monopole transitions can be associated with important aspects of nuclear structure, including
(i) volume oscillations (i.e. the so-called breathing mode), related to nuclear compressibility,
(ii) nuclear shape changes with effective radii variations (keeping constant the nuclear volume),
(iii) isotopic and isomer shift.
The Coulomb interaction of the nucleons with the electrons of an atomic shell or the Dirac background plays an important role to give rise to E0 transitions. Single photon E0 transitions are strictly forbidden by angular momentum conservation.

In the last decades a large number of experimental studies have been carried out to observe and characterize E0 transitions in atomic nuclei. The dimensionless monopole transition strength parameter, $\rho(E0)$, which carries all the information about the nuclear structure, can be determined from absolute transition rates. The dimensionless ratio of the B(E0) and B(E2) transition rates, $X(E0/E2)$ could be extracted from the experimental E0 and E2 intensities. E0 transitions between non-zero spin states are competing with E2 and M1 multipolarities further complicating the determination of $\rho(E0)$ and $X(E0/E2)$. Unfortunately the sign of $\rho(E0)$ could be determined only in a very few cases, it is customary to use $\rho^2(E0)$.

In this study a critical evaluation of the available experimental data on E0 transitions between $0^+$ states, for all even-even nuclei ranging from ${}^{4}_{2}\mathrm{He}_2$ to ${}^{250}_{98}\mathrm{Cf}_{152}$ has been carried out. For nearly 300 transitions adopted values of $\rho^2(E0)$, $X(E0/E2)$ and $q^2(E0/E2)$, defined as the ratio of the $I_K(E0)$ and $I_K(E2)$ intensities, have been deduced. In the current analysis the E2 transition to the first excited $2^+$ was used to determine $q^2(E0/E2)$ and $X(E0/E2)$. The emerging systematics of E0 transition properties will be compared with the systematics on E2 and E3 transitions.

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## [439] A New Tool to Interpolate Conversion Coefficients and E0 Electronic Factors

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Precise values of theoretical conversion coefficients, involving electrons and internal pairs plays an important role deducing transition multipolarities, mixing ratios, total transition intensities, etc. For more than 25 years the HSICC and HSMRG programs have been used for the Evaluated Nuclear Structure Data File (ENSDF). It was developed primarily to interpolate the Hager and Seltzer conversion coefficients [1]. Further improvement was made by using Dragoun, Plajner and Schmutzler [2] tabulation for the N+ shells. A web interface has been created, hosted by the National Nuclear Data Center at the Brookhaven National Laboratory, allowing access for a wider community.

Recently a more accurate and extensive conversion electron coefficient table has been published by Band et al. [3]. The U. S. Nuclear Data Program Meeting held at Brookhaven National Laboratory on November 6-7, 2003 recommended to adopt the new tabulations for the ENSDF.

We report on the development of the new program package, BRICC, which is being developed to calculate interpolated values of conversion electron coefficients for all atomic shells (K to R2) for Z=10 to 126. To improve the accuracy of the cubic spline interpolation procedure and to extend the tabulations for energies up to 6 MeV further calculations are required. Additional tabulations for pair conversion coefficients [4] as well as for E0 electronic factors [5] are also included in the new program.

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## [443] TESTING OF BROND-3 EVALUATIONS FOR FISSION PRODUCTS

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New evaluations of recommended neutron cross sections were performed for ruthenium, palladium, neodymium, and samarium isotopes included in the list of the most important fission-products. On the basis of these evaluations, the modified previous BROND-2 and FOND-2.2 files, and the revised files, recommended by the WPEC Subgroup 21, the new version of the BROND-3 library for fission products was compiled. The testing of BROND-3 files through available experimental benchmarks for fast reactors including some new results obtained with the IPPE BFS facility is discussed.

One-group radioactive capture, inelastic scattering and other reaction cross sections were calculated for the typical fast reactor neutron spectrum and compared with similar calculations for ENDF/B-6, JEF-3.0, and JENDL-3.3. A reduction in the spread of data from 5.9% to 1.6% for capture cross sections and from 10% to 5% for inelastic scattering cross sections is achieved relative to the results obtained previously by the WPEC Subgroup 17. The largest deviations for nuclides Pm-147 ($\sim$ 10%), Sm-151 ($\sim$ 25%), Xe-131 ($\sim$ 10%), Ag-109 ($\sim$ 10%), Ru-103 ($\sim$50%), Pd-108 ($\sim$20%), Xe-132 ($\sim$20%) are specially analyzed.

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## [448] Benchmark Testing of Zr for CENDL-3

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In the present paper the validation of zirconium evaluation from CENDL-3 were reported. Neutron leakage spectra experiment from 61-cm zirconium pile and HEU-COMP-INTER-001 criticality experiment were considered. Calculation results obtained with MCNP from CENDL-3, CENDL-2, BROND-2, ENDF/B-VI.2, JENDL-3.2 and JENDL-3.3 were compared. Underestimation of discrete inelastic scattering was observed. Slightly overestimate for (n, 2n) DDX and continuum inelastic cross section was also found in the calculated results based on natural zirconium of CENDL-3.

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## [450] TESTING OF NUCLEAR DATA FOR IRON, CHROMIUM AND NICKEL THROUGH A WIDE SET OF INTEGRAL EXPERIMENTS

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A set of experiments on BFS critical facility with different kinds of reflector filled by stainless steel and pure structure materials was fulfilled to study Fe, Cr and Ni neutron cross-sections in the fast energy region.

Measured traverses of uranium and plutonium fission reaction rates within the core and the reflector region were compared to the calculation results obtained by using different evaluations for Fe, Cr and Ni neutron cross-sections from BROND-2, FOND-2.2, ENDF/B-6, JENDL-3.2 and JENDL-3.3, JEF-2.2.

Additionally other types of experiments being performed in the past were involved to the analysis of Fe, Cr and Ni neutron cross-sections:

A. Integral experiments in well-known neutron spectra:

- Transmission measurements with $^{252}$Cf fission source in spherical geometry,
- Flat transmission measurements in so called "good" geometry.

B. Reactor physics experiments:

- Criticality and reactivity measurements in KBR critical assemblies in the media with k-infinite close to 1,
- Measurements of fission rate distribution in series of MASURKA, ZPR-3 and BFS-62 experiments with stainless steel reflector.

The comprehensive comparison of the analysis results and the observed discrepancies are discussed.

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## [460] Optical model parameters of alpha induced reactions on Ar-36.

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Nucleosynthesis and energy production in stellar environments depend critically on nuclear reaction cross sections. Alpha-induced reactions, in particular, play an important role in the helium burning stage of stars, novae, and supernovae. As part of an international collaboration, funded in part by the Civilian Research & Development Foundation, experimental data on elastic and inelastic scattering on Ar-36 were fitted using several optical model parameters. These parameters were used as input data for calculation of the Ar-36$(\alpha,\gamma)$ and Ar-36$(\alpha,n)$ cross sections performed using the statistical model code EMPIRE-2

code in the energy region of interest for astrophysical applications. The evaluations are stored in the ENDF format and will be made available to the community.

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## [466] Compound and Geometry-Dependent Pre-Compound Nuclear Models to Calculate the Nuclear Data for Fusion Reactors

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Compound and geometry-dependent precompound nuclear reactions are very useful concepts of nuclear theory to calculate cross-sections of neutrons around 14 MeV and below scattered by nuclei of material of installations producing energy of nuclear fusion. If these concepts shall be used to discuss and improve the experimental data they have to be completed by DWBA-type of contributions to the small step region of the incident neutrons which can account for the angular distribution of the scattered neutron, because there is the difficulty to separate experimentally the incoming from the scattered beam. The angle integrated cross-section in this region can be shown to be accounted for the surface dependent components of Blann's geometry-dependent precompound mechanism of the statistical state density and level density contribution of the compound and precompound components being calculated according to the recent developments by Anzaldo using the analytic number theory. The experimental data have been taken from the results by Hermsdorf, Meister, Sassonov, Seeliger, Seidel, and Shanin and Takahashi.

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## [473] Nuclear Data Evaluations for Americium Isotopes

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A recent highlight of nuclear data evaluation is for minor actinides such as americium isotopes, which is getting more important for nuclear technology applications, especially for nuclear transmutation, accelerator driven system, and high burn-up reactor calculations. In 2003, we re-evaluated the $^{241}$Am capture, (n,2n), and fission data by considering integral / differential experimental data. The new data of branching ratio to produce $^{242}$Am meta-stable state were tested against some integral quantities, and we still have a plan to improve capture and $\overline{\nu}_p$ data for $^{241}$Am.

In this study we describe recent upgrades of $^{241}$Am, $^{242g,m}$Am and $^{243}$Am data in the keV – 30 MeV range, to take advantage of recent measurements and advances in calculational modeling methods which are especially important for nuclides where few measurements are available. A new $^{240}$Am evaluation is also needed — this presents a particular challenge for nuclear theory, since no measurements exist owing to its short half-life (50.8 hours). The nuclear model code GNASH is extensively used for our evaluations, by adjusting nuclear model parameters to reproduce the experimental data available.

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## [480] On the quality of ENSDF $\gamma$-ray intensity data for $\gamma$-spectro-metric determination of Th and U and of disequilibria in their decay series, in the assessment of the radiation dose rate in luminescence dating of sediments

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Advanced thermally and optically stimulated luminescence (TL, OSL) dating protocols are becoming prominent geochronometric tools for the age determination of sediments [1,2], expected to lead — for aeolian loess deposits — to a significantly enhanced knowledge in the fields of palaeoclimatology and -ecology. In luminescence dating, the radiation dose rate should be reliably known, its uncertainty being linearly propagated to the age result. Among the techniques used for dose rate determination [3], a special role is played by Ge $\gamma$-ray spectrometry of the sediment. It not only yields the content (and thus the dose rates) of the radioelements K, Th and U, but it also allows measuring $^{228}$Ac, $^{224}$Ra, $^{212}$Pb and $^{208}$Tl in

the $^{232}$Th decay series, and $^{234}$Th, $^{214}$Pb, $^{214}$Bi and $^{210}$Pb in the $^{238}$U series. This provides information on the occurence — in geological times — of possible disequilibria, which are especially likely in the $^{238}$U series due to $^{226}$Ra-mobility (for which $^{214}$Pb and $^{214}$Bi are the indicators) and/or $^{222}$Rn-emanation (with $^{210}$Pb as the indicator). Such disequilibria — if significant — are deteriorating the accuracy of the radiation dose rate estimation and hence of the dating result.

In the present work, the performance is examined of two methodological variants of the $\gamma$-spectrometric analyses, which are largely depending on the quality of the nuclear decay data involved. Firstly, the possibility is investigated of a parametric calibration of the sediment measurements. Evidently, this requires the detection efficiency (together with coincidence summing effects) to be reliably known, and furthermore its accuracy is depending on the $\gamma$-ray intensities to be introduced. Actually, a parametric calibration could be preferred to the usually applied relative one with K/Th/U standards, which should be remeasured for each new sample geometry, and the composition and packing density of which are occasionally not matching those of the samples, thus necessitating a detection efficiency conversion anyhow. The second one concerns the check of the $^{226}$Ra disequilibrium. Although, as said, this can be based on $^{214}$Pb and $^{214}$Bi, the latter can also be formed via decay of $^{222}$Rn surrounding the Ge-detector (unwanted, and usually flushed with $N_2$ from the Dewar). Therefore, an interesting alternative would be to directly measure the $^{226}$Ra 186.1 keV $\gamma$-ray, an intense line in the spectrum, which is however heavily interfered by $^{235}$U at 185.7 keV. In principle, corrections can be made via other lines in the spectrum (some involving second-order corrections), thus relying on the introduction of $\gamma$-ray intensities (next to detection parameters), the quality of which is largely influencing the reliability of the result obtained.

The above-described methodologies were examined via the measurement of several loess and sand sediments, and with introduction of $\gamma$-ray intensity data originating from ENSDF (via Isotope Explorer [4]). Relevant conclusions could be drawn as to the accuracy of the data and their quoted uncertainties, and — as a feedback to the experimentalists and evaluators of the nuclear data under study — some recommendations could be formulated.

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## [482] R-Matrix Analysis of the $^{14}$C System

T. N. Massey, J. F. Guillemette, S. M. Grimes, J. E. O'Donnell

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Data for neutron scattering on $^{14}$C and for the $^{10}$Be$(\alpha, n)^{13}$C reaction have ben subjected to an R-Matrix analysis. A number if deficiencies in the fit were noted when the conventual approach to fitting was used. Two additional techniques have been introduced to improve the fits. Level spins, parities and spectroscopic factors were obtained from a shell-model calculation. These were then used to determine starting R-matrix parameter values. A better R-matrix fit was obtained by this method. In addition, a random walk search procedure was introduced. Though not highly efficient, use of this procedure over forty eight hour periods greatly improved the results.
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# Poster D

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359 The ENSDF java package
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361 New Web-Based Access to Nuclear Structure Datasets
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385 Integral Validation of Minor Actinide Nuclear Data by using Samples Irradiated
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472 Verification of MENDL2 and IEAF-2001 Data Bases at Intermediate Energies
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## [223] Development of a Methodology for Analysis of the Fe-56 ENDF-B/VI Cross Sections with a Time-of-Flight Experiment

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An accurate determination of the cross section data contained in the Evaluated Nuclear Data Files (ENDF) is vital in performing accurate particle transport simulations in a wide range of applications. This paper discusses a methodology developed for analysis of a time-of-flight (TOF) experiment performed for examination of iron cross sections. The methodology combines measurements from several experimental setups and corresponding Monte Carlo simulations.

The neutron TOF spectra were measured using the spherical-shell transmission method with iron shells of two different thicknesses and two neutron generating interactions for various beam angles. In this study we have considered N (p, n) and D (d, n) interactions for different beam angles including 0, 15, 30, 45, 60, 90, and 135 degrees. The experimental spectra were utilized to obtain a source distribution for Monte Carlo simulation of the iron shell experiments. Our results indicate that the angular distribution of the source reaction is very important for this work. The validity of this source distribution was tested.

Comparison between Monte Carlo predictions and TOF measurements identified discrepancies over several energy ranges that have been attributed to inaccuracies in the Fe-56 inelastic scattering cross section. To estimate the impact of the Fe-56 cross sections' inaccuracies on the measured spectra, we developed a utility code (XSMOD) for modifying the cross section data in the ENDF-B/VI library. XSMOD allows for any user-defined changes to cross section values at different energy ranges. Hence, using XSMOD, we modified the original ENDF-B/VI data, and performed Monte Carlo calculations to examine the predicted neutron spectra as compared with measured spectra.

Different cases in which the inelastic cross sections were decreased by various percentages in different energy ranges were examined. It was noted that the total cross section is accurate, hence as inelastic cross sections were changed, the elastic cross sections were changed oppositely so that the total cross section remained unchanged.

The results of these new calculations indicate that the modified cross sections yield significant reductions (as large as $\sim$40%) in the discrepancies between experimental and calculation spectra. This finding suggests that our methodology may be an effective approach for identifying regions of concern for cross section work. Further, a preliminary study using the multigroup form of the modified cross sections has shown significant impact on reactor pressure vessel fluences.

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## [260] Comparisons of Neutron Cross Sections and Isotopic Composition Calculations for Fission Product Evaluations

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The neutron absorption cross sections for 18 fission products evaluated within the framework of the KAERI (Korea Atomic Energy Research Institute)-BNL (Brookhaven National Laboratory) international collaboration have been compared with the ENDF/B-VI release 7. Also, the influence of the new evaluations on isotopic composition calculations of the fission products has been estimated through the OECD/NEA burnup credit criticality benchmarks (Phase 1B) and the LWR/Pu recycling benchmarks. These calculations were performed by WIMSD-5B with the 69 group libraries prepared from three evaluated nuclear data libraries: ENDF/B-VI.7, ENDF/B-VI.8 including new evaluations in resonance region covering thermal region (the first stage evaluations finished in 2000), and ENDF/B-VII expected including those in upper resonance region up to 20 MeV (the second stage evaluations finished in 2003). For Xe-131, the composition calculated with ENDF/B-VI.8 shows maximum difference of 4.78% compared to ENDF/B-VI.7. However, the isotopic compositions of all fission products calculated with ENDF/B-VII expected shows no differences compared to ENDF/B-VI.7 for the thermal reactor benchmark cases.

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## [268] Development of Nuclear Reaction Data Retrieval System on IntelligentPad by Japan Charged Particle Reaction Data Group

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A newly designed retrieval system of nuclear reaction data [1] is developed on the IntelligentPad architecture. for NRDF (Nuclear Reaction Data File)[2] and EXFOR (EXchangeFORmat) compilation, is applied as an application example. We designed the network-based (client-server) retrieval system. The server system is constructed on a UNIX workstation with a relational database, and the client system is constructed on Microsoft Windows PC using an IntelligentPad software package. Our system is called CONTIP, which is an abbreviation of "Creative, Cooperative and Cultural Objects for Nuclear data and Tools". We will develop CONTIP to realize effective utilization of nuclear reaction data: I. "Reproduction, Re-edit, Re-use", II. "Circulation, Coordination and Evolution", III. "Knowledge discovery".

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## [277] JANIS-2.0 an improved version of the NEA Java-based

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The first version of the JANIS nuclear data display software, developed by the OECD Nuclear Energy Agency (NEA), was released in conjunction with the nuclear data conference ND'2001 in Tsukuba, Japan. More than 700 copies have been distributed since then and users have provided feedback and ideas for further development. This feedback was used in the development of a new version, which implements several improvements such as:

- Management of the data through a Java-based relational database management system.
- Access to centralised reference databases (available on the NEA server) through the Java servlet technology.
- Access to experimental reaction data in the original EXFOR format. The first version of JANIS accessed only the numerical EXFOR data through a special computational format. In the new version, the user can access the full EXFOR work, including the comment section.
- Access to bibliographic references in the CINDA database for neutron induced reaction data, including a link between CINDA and EXFOR.
- Access to nuclear and decay properties (NUBASE).
- Generalisation of computational features available for reaction datafor interaction data; these features (such as linear combinations, ratios of data) were earlier restricted to cross-section data only. It is now possible to perform more advanced combinations such as a product of cross-sections with energy and angular distributions.

The full paper will show how the features of JANIS-2.0 can be used to visualise and explore the diversity of information contained in nuclear data libraries.

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## [279] Use of Integral data to improve the European Activation File

Robin A. Forrest[1], Pavel Bem[2], Jiri Kopecky[3], Ulrich Mollendorff[4], Mario Pillon[5], Klaus Seidel[6], Stanislav P. Simakov[7], Jean-Christophe Sublet[8]

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The European Activation File is the source of nuclear data for fusion activation calculations that has been developed in Europe. In order to trust the calculations made with the data, validation is essential. A key part of this is the comparison of the EAF data with integral experiments made in fusion relevant spectra on a wide range of materials. A review of the results for the EAF-2001 and -2003 libraries is given, leading on to the recent work on the test library EAF-2004. The latter is innovative in extending the upper energy range from 20 to 60 MeV. Although integral data above 20 MeV are scarce, recent measurements have meant that a start at these energies can be made. Examples of reactions that are considered to be validated are given, this requires that both the integral and differential data are consistent with the EAF data. Cases where integral data are good but differential data are lacking or discrepant are highlighted, as are cases where both types of experimental data differ from EAF.

The methodology for the use of measurements of the activity and heat to extract effective cross sections and the use of these to present C/E plots is detailed. This technique has the advantage that the integral data can be used during EAF library development rather than only when the library has been finalised. The improvement of the EAF cross section data in the various versions of the library is demonstrated.

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## [311] Validation of IRDF-2002 Dosimetry Library on FNG-Series of Benchmark Experiments

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Data Development Project of the International Atomic Energy Agency (IAEA) aimed at updating the library of dosimetry cross sections IRDF-2002 was completed recently. Within this project the IRDF-90 library was reviewed and updated using source data from the JENDL-99/Dosimetry File and the Russian Reactor Dosimetry File (RRDF). Several reactions in RRDF were revised or improved within the scope of this project.

The new IRDF-2002 file was applied in the analysis of several benchmark experiments performed at the Frascati Neutron Generator (FNG):
- FNG-ITER Blanket Bulk Shield
- FNG Silicon Carbide
- FNG Tungsten

These benchmark experiments involved several reaction rate measurements covering fast to thermal neutron energy range, like Au-197(n,g), Mn-55(n,$\gamma$), In-115(n,n'), Ni-58(n,p), Fe-56(n,p), Al-27(n,$\alpha$), Ni-58(n,2n), Zr-90(n,2n) and Nb-93(n,2n). The analyses included both the comparison of the measured and calculated reaction rates as well as the uncertainty estimations based on the corresponding cross-section covariance matrices. To determine the progres achieved with the new file the results were compared to those using the IRDF-90 data.

The main purpose of repeating the calculations with the new dosimetry cross sections was to check for any improvement between measured and calculated reaction rates (compared to IRDF-90) and removal of some inconsistent trends in the results for different monitors. The results represent an indirect validation of the new IRDF-2002 dosimetry library.

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## [313] Web-Based Utility System for Nuclear Reaction Data

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Japan Charged-Particle Nuclear Reaction Data Group (JCPRG) belongs to Nuclear Reaction Data Center Network (NRDC), and has compiled Japanese experimental charged particle nuclear reaction data base described in Nuclear Reaction Data Format (NRDF) and in Exchange Format(EXFOR). JCPRG has developed systems to utilize NRDF files [1,2,3]. One of the achievements of JCPRG with relation to the web-based utility system is the release of a new retrieving and plotting engine (DARPE) for NRDF in 2003 (See `http://www.jcprg.org/`).

JAERI Nuclear Data Center is also a member of NRDC and has developed Japanese Evaluated Nuclear Data Library (JENDL) with the aid of Japanese Nuclear Data Committee. The newest version of JENDL is JENDL-3.3 [4] which covers neutron-induced reactions for 337 nuclides and $10^{-5}$ to 20 MeV of incident neutron energy.

The formats for experimental and evaluated nuclear data files (e.g. EXFOR and ENDF format) are designed to record various types of data. Users may feel difficult to use them as they are, since they include some unfamiliar terminologies and particular format and procedures. Therefore, it should be convenient to develop tools for general purpose utility such as retrieval and plotting, which can reduce the distance between files and end users. Of course, expert users of EXFOR and ENDF format can utilize evaluated data and experimental data without any difficulties. However, the general users are not familiar with current utility codes.

JCPRG and JAERI started a new joint project to develop new utility system for the experimental data and evaluated data. For users' availability, an internet browser (e.g. Internet Explorer and Netscape), which most users are familiar with, is chosen as a client interface between the databases and users. Users are able to search any data they want and obtain image files of them, by submitting queries to the database server on the web page without any requirement of additional software installation. The preliminary version of the server side CGI script is now working.

[1]M. Chiba *et al.*, Journal of Information Science 12(1986)153.
[2]Y. Ohbayasi *et al.*, Journal of Information Science 26(2000)29.
[3]Y. Ohbayasi *et al.*, Journal of Nucl. Sci. Tech., Suppl., 1(2000)566.
[4]K. Shibata *et al.*, Journal of Nucl. Sci. Tech. 39(2002)1125.

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## [324] The United Kingdom Nuclear Science Forum

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The United Kingdom Nuclear Science Forum (UKNSF) brings together the measurers, evaluators and users of nuclear data throughout the United Kingdom. Its members, including representatives from the nuclear industry, the regulators, government departments and academia, have interests in both neutron cross-section data and decay scheme data. The forum meets formally once a year, while, between meetings, business is carried out by e-mail and via the forum's web site. The UKNSF acts as an interface between the UK nuclear data community and international nuclear data centres such as the OECD Nuclear Energy Agency Data bank and the Nuclear Data Section of the International Atomic Energy Agency. The forum also acts as a link between regulators, data users and data measurers to assist in establishing UK policy with respect to data issues. The UKNSF aims to engender and disseminate

expertise in measuring, evaluating, processing, testing and using nuclear data in the UK. It provides peer-review for reports of measurements, evaluations and tests of basic nuclear data and identifies programmes of work to improve the quality of nuclear data libraries.

The paper will describe the recent activities of the UKNSF and will review some of the work covered by recent UKNSF technical papers.

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## [326] Verification of Monte Carlo Calculations by means of Neutron and Gamma Fluence Spectra Measurements behind and inside of Iron-Water Configurations

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Gamma spectrum measurements in neutron-gamma reactor environments, suitable to test coupled neutron-gamma transport calculations, are very rare or not available at all. Considering recent findings on possible gamma-induced radiation damage in the pressure vessel region and the following new interest in gamma fluence spectra, a new neutron-gamma experiment has been realized. At the zero-power research reactors AKR of the Technical University Dresden and the ZLFR of the University of Applied Sciences Zittau/Goerlitz neutron and gamma spectra have been measured behind and inside of transmission modules consisting of variable iron and water slabs*). The calibrated NE213 scintillation spectrometer allowed the simultaneous measurement of absolute gamma and neutron fluence spectra in the energy range 0.5 - 10 MeV for photons and 1.0 - 10 MeV for neutrons. The reactor power was determined with the help of in-core activation and fission detector measurements and their Monte Carlo simulation.

With main emphasis on the gamma radiation, the results of gamma and neutron fluence measurements were compared with Monte Carlo calculation results. In a first step, absolute neutron source distributions were calculated by normalizing MCNP calculation results by in-core detector measurements. Using the neutron sources and the reactor power history the gamma source distributions in the core were obtained. Based on the resulting absolute neutron and gamma source distributions neutron and gamma fluence spectra integrated over the NE213 detector volume were calculated by means of the codes TRAMO and MCNP using ENDF/B-VI and other nuclear data files. The comparison of results of both codes, of results obtained with different evaluated libraries and of calculated results with experimental data, aims at the estimation of the uncertainties of up-to-date neutron-gamma calculation methods and associated nuclear data libraries.

*) B. Boehmer et al., Proc. of ND2001, Journ. Nucl. Sci. Technol. (JNST), Suppl. 2, Vol. 2, p. 947-950 (August 2002)

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## [329] Measurements of Thermal Neutron Flux and Capture Induced Gamma Radiation Spectra behind and inside of Iron-Water Slabs and Comparison with Monte Carlo Results

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There is a strong interest in neutron and gamma induced radiation damage in nuclear reactor materials. In order to verify the origin of the high-energy part of the gamma-ray spectrum, recent simultaneous measurements of neutron and gamma energy spectra by means of a NE-213 scintillator inside and behind of various arrangements of iron and water slabs*) were supplemented by an HPGe detector behind the arrangements allowing high-resolution gamma measurements. As a result, the whole high-energy part (above 5 MeV) of the gamma ray spectrum could be ascribed to thermal neutron capture.

Consequently, as an extension of the experiment, special attention was payed to determine experimentally the thermal neutron fluence as the major source of high energy photons by means of an absolutely calibrated He-3 proportional counter and a fission chamber. The thermal neutron fluxes were measured behind (and sometimes inside of) the experimental arrangements. The experimental results were compared to Monte Carlo calculations in order to evaluate the accuracy of codes and nuclear data for that problem.

*) B. Boehmer et al., Verification of Monte Carlo Calculations by Means of Neutron and Gamma Fluence Spectra Measurements behind and inside of Iron-Water Configurations, another contribution submitted to this conference

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## [347] The Triangle Universities Nuclear Laboratory Nuclear Data Evaluation Program

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The Nuclear Data Evaluation Group at Triangle Universities Nuclear Laboratory (TUNL) is responsible for evaluating information relevant to nuclei in the A=2-20 mass range. Following the retirement of Fay Ajzenberg-Selove, TUNL assumed the responsibility for updating reviews of "Energy Levels of Light Nuclei: A=3-20" and for maintaining the corresponding ENSDF files which include a comprehensive compilation of nuclear properties, such as "Adopted Levels and Gammas" and reaction and decay information. Physics interests at TUNL, which are in part centered around low-energy light ion-beam facilities, provide a healthy environment for evaluation and review of nuclei in this mass region. The TUNL nuclear data evaluation group has emphasized the World Wide Web as a means for dissemination, and our priority activities are to provide abridged versions of the "Energy Levels of Light Nuclei" reviews in PDF/HTML formats. In this contribution we will provide an overview of resources for A=3-20 nuclei that are available from our website.

This effort is supported by the United States Department of Energy under Grant No.'s DE-FG02-97ER41033 and DE-FG02-97ER41042.

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## [354] Nuclear Science References as a Tool for Data Evaluation

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For several decades, the Nuclear Science References (NSR) database has been maintained as a tool for data evaluators and for the wider pure and applied research community. NSR is an indexed bibliography of primary and secondary references in nuclear physics research. The database is updated on a continuing basis; approximately 4200 references are added each year.

Most NSR entries include a keyword abstract, which provides a brief summary of the paper's contents. This abstract serves two purposes; it is used to index the entries for efficient retrieval, and helps the user decide whether the retrieved reference is of interest in his or her research.

This talk will discuss the scope and structure of the database, and recent changes in its administration and dissemination. Planned improvements to the database will also be discussed.

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## [357] NuDat 2.0: Nuclear Structure and Decay Data on the Internet

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NuDat 2.0 is a software product developed by the National Nuclear Data Center (NNDC). It provides an interface between web users and several NNDC nuclear structure and decay databases. NuDat 2.0

is based on a fast Linux computer running the Apache Tomcat web server; it replaces an earlier, open VMS-based version. NuDat 2.0 can be used to search for ground and excited states level properties (energy, half-life, spin and parity, decay modes), gamma-ray information (energy, branching ratio, multipolarity, coincidences) and decay radiation information (energy, intensity, dose). In addition to the search capabilities, an interactive chart of nuclei is displayed. The basic data for NuDat 2, derived from the ENSDF and Nuclear Wallet Cards files, are stored in relational databases; a number of Java Server Pages files perform the interaction between the user and the databases. Different examples highlighting NuDat 2 search capabilities and display options are presented.

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## [359] The ENSDF java package

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A package of computer codes has been developed to process and display nuclear structure and decay data stored in the ENSDF (Evaluated Nuclear Structure Data File) library. The codes were written in an object-oriented fashion using the java language. This allows for an easy implementation across multiple platforms as well as deployment on web pages. The structure of the different java classes that make up the package is discussed as well as several different implementations.

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## [361] New Web-Based Access to Nuclear Structure Datasets

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As part of an effort to migrate the NNDC databases to a relational platform, a new web interface has been developed for the dissemination of the nuclear structure datasets stored in the ENSDF (Evaluated Nuclear Structure File) and XUNDL (Experimental Unevaluated Nuclear Data List) databases.

The new interface provides greater power and flexibility in the selection of data than was previously available on the web. It allows searching and filtering on indexed reaction and decay quantities, as well as nuclide mass and charge. Searches can be limited to one of the databases, or can span both.

Cross-referencing with the Nuclear Science References database (NSR), allows retrieval of all papers referenced by a given structure dataset, or retrieval of all datasets referencing a specific paper.

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## [385] Integral Validation of Minor Actinide Nuclear Data by using Samples Irradiated

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Japan Atomic Energy Research Institute (JAERI) has been developing technologies for partitioning and transmutation of long-lived nuclides in high-level radioactive waste. In the dedicated transmutation systems, reliable neuclear data of minor actinide (MA) are indispensable to obtain a reliable design of a transmutation system. Present status of MA nuclear data is not so satisfactory. To obtain reliable nuclear data of MA, significant efforts are needed not only for differential measurement of MA but also for the validation of reliability of existing data by using integral measurements. As such an effort, radiochemically analyzed data of the actinide samples irradiated at the Dounreay Prototype Fast Reactor (PFR) were used in this study. The samples were actinide oxides of 21 different isotopes from thorium to curium. In the present work, the burnup calculations were performed and the calculated results were compared with the experimental data to validate the reliability of neutron cross section data of MA in an evaluated nuclear data file JENDL-3.3, ENDF/B-VI, and JEFF-3.0.

The ORIGEN code was used for the calculational analysis of the irradiated samples. The 6 groups neutron spectra and the flux values, which were reported in the ORNL document, were used for the sample burnup calculations. For the cross sections of the samples, revised JAERI Fast Reactor Group Constant Sets (JFS-3) based on JENDL-3.3, ENDF/B-VI, and JEFF-3.0 were utilized. These 73-group

libraries wer then collapsed to a 6-group library corresponding to the 6-group described above. The one-group cross sections were calculated for the each PFR run using this 6-group library with the 6-group flux spectra for each reactor run.

The systematic validation of actinide cross section was given by the burnup calculation of actinide samples irradiated at PFR. Chemically analyzed data of actinide samples irradiated 492 days at PFR provides a variable database for integral evaluation of MA cross sections. We hope our data will be used widely to improve the reliability of MA cross sections.

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## [386] IRIS PIN CELL AND FUEL ASSEMBLY BENCHMARK INTERCOMPARISONS

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Validation plays a central role in the improvement of reactor physics codes and associated nuclear data libraries, as well as in the assessment of the accuracy of calculations. The nuclear data libraries can be sometimes adjusted to reduce the discrepancies. However, for the adjustments to be generally valid it is important to demonstrate that the numerical methods and physics models provide an accurate treatment of all the complexities of the systems. Estimates of the uncertainties arising from approximations in the methods used in different nuclear data processing and neutron transport codes can be obtained by intercomparing calculations made using different code systems. Depletion calculations made for simplified reactor configurations using both deterministic and stochastic methods, with different degrees of refinement in the modelling, could be intercompared using the same source of nuclear data. In this way, the accuracy of the different methods used at various stages, ranging from nuclear data processing systems to neutron transport calculations, can be assessed

This study is based on four depletion code systems: (a) MCNP-4C and ORIGEN2.1 interfaced by the MOCUP driver; (b) recently developed procedure based on KENO-V.a and ORIGEN2.1; (c) design-oriented procedure based on the SAS2H control module from SCALE-4.4a and an structured approximate geometrical model, which uses a simplified unit fuel within an infinite lattice for the fuel burnup analysis; and (d) WIMSD5 with recently released multigroup libraries.

The major advantage of using KENO-V.a/ORIGEN2.1 procedure is the decrease in computation time by a factor of about 20 as compared with MOCUP. In both, the MCNP-4C/ORIGEN2.1 and KENO-V.a/ORIGEN2.1 reference procedures, the same fuel burnup model was applied, i.e., the model with 95 most important fission products. Also, in the both reference procedures an improvement of radioactive capture (n, g) reactions with a product nuclide in an excited (metastable) nuclear state for all light-elements, actinides and fission products was inserted.

This paper presents a detailed study of the differences between depletion analysis results for the IRIS light water reactor pin cell models obtained using the four code systems. The leakage has been assumed to be zero, but a cell with leakage treated by means of a buckling has also been analysed. Cases at different temperatures have been calculated and the temperature coefficient calculations are also compared. Differences in the results between square and cylindrical cell boundary conditions have been studied and shown to be important.

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## [390] Group Constants Generation of the Pseudo Fission Products for Fast Reactor Burnup Calculations

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Generally burnup calculations of fast reactors are performed with the lumped fission product of each actinide. 172 fission products based on ENDF/B-VI were selected for generation of the pseudo fission product cross sections of each actinide such as U235, U238, Pu239, Pu240, Pu241 and Pu242. The cross sections of 172 nuclides were generated at 400 K and 850 K with the NJOY code. The burnup chains of 172 nuclides were made to use the cumulative or independent fission product yield data for weighting the cross section data of 172 nuclides. The pseudo fission product cross section sets of the 6 actinides were prepared with MATXS-format of 80 energy groups. The MATXS-format cross sections can be easily

transformed to the other form such as ISOTXS-format using the TRANSX code. Each lumped cross section includes the elastic, inelastic scattering and capture cross sections.

This paper will describe the generation process of the pseudo fission product cross sections for fast reactor analyses. The burnup chains of 172 nuclides, procedure of the lumping the cross sections and how to use the sets will be included.

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## [396] Benchmark results for delayed neutron data

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We test the quality of the delayed neutron data in the most recent nuclear data libraries, by calculating the effective delayed neutron fraction ("beta-effective") for many benchmark systems. The results are obtained by means of a recently developed Monte Carlo method, which is implemented in a version of MCNP-4C3. A major advantage of this method is that it requires only a single run of MCNP to determine beta-effective. In fact, this is the same run with which one calculates k-effective. In doing so, the value for beta-effective is based directly on the nuclear data, without the need for additional pre- or post-processing. This enables fast and reliable computation of the effect of the delayed neutron data on beta-effective for many benchmark systems. We illustrate this point by presenting results for the most recent nuclear data evaluations available.

Moreover, this method gives values for the fundamental delayed neutron fraction, beta-0, and for beta-effective, in all available time groups (e.g. the traditional 6 groups, or, as is proposed for JEFF-3.1, 8 groups). By comparing results, based on different nuclear data evaluations, for beta-0 and beta-effective for all time groups, one can quantify the influence of both delayed neutron yield and delayed neutron spectrum for each time group.

This benchmarking effort ties in to other benchmarking work, such as for criticality, for spectral indices, and for shielding. We report results for these benchmarks as well, in order to work towards a more complete validation of nuclear data libraries.

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## [400] Nuclear Information Services at the National Nuclear Data Center

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The National Nuclear Data Center (NNDC) has been providing remote access to the nuclear physics databases it maintains and to other resources since 1986. Access was originally *via* DECNET and modem; then, TELNET; and now primarily *via* the Web. Since about 1999, the NNDC and collaborators from the IAEA have been migrating the databases from the original CODASYL-DBMS software to a modern relational database system. The Web interfaces to these databases have also been upgraded to use SQL, jsp, and Java servlets. Other NNDC Web pages have also been upgraded to provide a better and more consistent style. The improved services available from the NNDC will be described along with the other resources available on the NNDC Web site (http://www.nndc.bnl.gov).

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## [403] EVALUATED NUCLEAR STRUCTURE DATA FILE and RELATED PRODUCTS

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The Evaluated Nuclear Structure Data File (ENSDF) is a leading resource for the experimental nuclear data. It is maintained and distributed by the National Nuclear Data Center, Brookhaven National Laboratory. The file is mainly contributed to by an international network of evaluators under the auspice of the International Atomic Energy Agency. Current membership of the network includes scientists from Australia, Argentina, Belgium, Brazil, Bulgaria, Canada, China, France, India, Japan, Kuwait, Russia and the United States.

The ENSDF is updated, generally by mass number, i.e., evaluating together all isobars for a given mass number. If, however, experimental activity in an isobaric chain is limited to a particular nuclide then only that nuclide is updated. The evaluations are published in the journal Nuclear Data Sheets, Academic Press, a division of Elsevier.

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## [407] EXFOR/CINDA/ENDF: migration of databases to give higher quality nuclear data services

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Extensive work began in 1999 to provide migration capabilities for the EXFOR, CINDA and ENDF nuclear reaction databases, and convert the available nuclear data services from VMS to a modern computing environment. This work has been performed through co-operative efforts between the IAEA Nuclear Data Section (IAEA-NDS) and the National Nuclear Data Centre (NNDC), Brookhaven National Laboratory. A main goal of the project was to implement databases in a relational form that provide full functionality for maintenance by data centre staff and improved retrieval capability for external users. The project also afforded the opportunity to make general revisions and improvements to the nuclear reaction data services by taking account of past experience with the old system and users' feed back.

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## [414] NNDC Stand: Activities and Services of the National Nuclear Data Center

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The NNDC stand will be prepared in a form of major poster to be on display for the duration of the whole conference. The stand aims to give an overview of the NNDC activities and recently upgraded data services.

The National Nuclear Data Center (NNDC) collects, evaluates, and disseminates nuclear physics data for basic nuclear research, applied nuclear technologies and for national security. The NNDC provides coordination for US Nuclear Data Program and CSEWG, maintains and contributes to the nuclear structure (ENSDF, NSR, XUNDL) and nuclear reactions (ENDF, CSISRS, CINDA) databases along with several derived databases, and prepares for publication Nuclear Data Sheets and Nuclear Wallet Cards.

Recently, the NNDC migrated US Nuclear Data Program databases and Web Services from an Oracle/VMS to a Sybase/Linux production environment. The new Web-based nuclear data retrieval system is tightly integrated with nuclear structure and reactions evaluations and compilation efforts.

Nuclear Structure Data Services were significantly upgraded to improve capabilities and user friendliness for ENSDF and NSR databases. The new ENSDF Web Services significantly improve and simplify ENDSF nuclear data set retrievals. The new NuDat Web Services enhance search and formatting capabilities for nuclear data, and provide more convenient way to search for levels and gammas.

Nuclear Reaction Data Services were substantially upgraded to provide a better access to reaction data compilations and evaluations. New Web interfaces for CSISRS and ENDF databases, developed in collaborative effort with the IAEA Vienna, provide wide range of options for data retrievals and analysis using standard and interpreted formats as well as graphic tools.

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## [425] Neutron Cross Section Evaluations for $^{70,72,73,74,76}$Ge

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Neutron cross section evaluations were performed for all stable and long-lived isotopes of Germanium, $^{70,72,73,74,76}$Ge, up to 20 MeV. The work was motivated by the need to fill-in the gap in current evaluations that do not provide photon production data. These data are of importance for Monte Carlo simulation calculations of detector systems, and thus of relevance also to homeland security applications.

Evaluations were done separately in resonance and fast neutron energy regions. Current resonance evaluations were updated as a part of the ongoing BNL-325 re-evaluation effort. At higher energies, EMPIRE model code reaction system was employed. Calculations were validated against experimental data whenever available, including well measured photon production for n + Fe. ENDF-6 formatted files were prepared and submitted for inclusion into a new version of the United States ENDF/B library, ENDF/B-VII.

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## [428] Review of Neutron Cross Section Evaluations for Fission Products

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Review of neutron cross section evaluations for fission products (Z = 31 - 68) included in 5 major evaluated nuclear data libraries was performed. The aim of the project, conducted under the WPEC Subgroup 21 collaboration during 2001 - 2004, was to prepare recommendations for best evaluations for the bulk of fission products. Altogether, reviewed were evaluations for 211 materials.

Considered were libraries ENDF/B-VI.8, JEFF-2.2, JENDL-3.3, BROND-2.2 and CENDL-3.0. Review methodology treated separately low energy and fast neutron energy regions. Graphical intercomparison was prepared for evaluations from 5 libraries against experimental data from the CSISRS library. Taken into account was methodology used in various evaluations. The review focused on microscopic data, no attempt to use integral data was made.

Results show that majority of recommedations are for the two libraries that use fairly new evaluations. In both low and fast energy regions, JENDL-3.3 is mostly recommended. This is followed by CENDL-3 in the fast energy region.

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## [435] Nuclides.net: A Web-based Environment for Nuclear Data and Applications

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Nuclides.net is an interactive multimedia tool based on the latest internet technology. The software provides an integrated environment for computations on radionuclides and their radiations. It has been developed by scientists working on a daily basis with radionuclides and is aimed at both students and

professionals for reference data on radionuclides and calculations based on this data. The main emphasis of Nuclides.net is on nuclear science applications using international evaluated data. It is particularly suitable for educational purposes in the nuclear industry, health physics and radiation protection, nuclear and radiochemistry, nuclear physics, astrophysics, etc.

From a powerful, user-friendly interface, the Nuclide Explorer, the user can navigate through the nuclide chart. Among the multiple features, such as dosimetry and shielding calculations, a large amount of data is available to the user. This data comes from internationally recognized sources and provides nuclear information on 3650 ground states and isomers, including fact-sheets, cross-sections, fission products and yields, from a simple mouse click.

The basic radioactive decay data used in the nuclides.net database is from the NUBASE evaluation. The evaluation contains experimentally known nuclear properties, and some that have been estimated from extrapolation, for approximately 3650 nuclides: mass, isomeric excitation energy, half-life, spin, parity, decay modes and intensities.

The effective dose coefficients have been taken from the International Commission for Radiological Protection ICRP reports.

Spectral data is from the Joint Evaluated File (JEF) version 2.2, with a few corrections for known inaccuracies in the file.

Averaged cross section data are based on JEF-2-2, ENDF/B-VI, JENDL-3.2, BROND-2, and CENDL-2. Additional graphs of point-wise cross-sections based on JENDL3.2 have recently been added.

Fissions yield data are from: JENDL-3.2, JEF-2/FPY and ENDF/B6 data files.

Nuclides.net is web server based tool, which, therefore, allows it to be updated with the latest data files when available.

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## [472] Verification of MENDL2 and IEAF-2001 Data Bases at Intermediate Energies

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The work presents results on computer simulations of two experiments whose aim was measuring the threshold activation reaction rates in $^{12}$C, $^{19}$F, $^{27}$Al, $^{59}$Co, $^{63}$Cu, $^{65}$Cu, $^{64}$Zn, $^{93}$Nb, $^{115}$In, $^{169}$Tm, $^{181}$Ta, $^{197}$Au, and $^{209}$Bi thin samples placed inside and outside a 0.8-GeV proton-irradiated 4-cm thick W target and a 92-cm thick W-Na composite target of 15-cm diameter both. In total, more than 1000 values of activation reaction rates were determined in both experiments. The measured data were compared with results by the LAHET code using several nuclear data bases for the respective excitation functions, namely, ENDF/B6 for cross section of neutrons at energies below 20 MeV and MENDL2 together with MENDL2P for cross sections of protons and neutrons of 20 to 100 MeV energies. The recently developed IEAF-2001 data base that provides neutron cross sections up to 150 MeV was used as well. Simulation-to-experiment results obtained using MENDL2 and IEAF-2001 are presented. The agreement between simulation and experiment was found satisfactory for both data bases. Nevertheless, further studies should be conducted to improve simulations of the production of secondary protons and high-energy neutrons, as well as the high-energy neutron elastic scattering. Our results allow drawing some conclusions concerning the reliability of the transport codes and data bases used to simulate Accelerator Driven Systems (ADS), particularly with Na-cooled W targets. The high-energy threshold excitation functions to be used in activation-based unfolding of neutron spectra inside the ADS can be also inferred from our results.

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## [481] Nuclear Data Online Services at Peking University

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The online services of China's nuclear science and industry field via the Internet have quickly grown since 1990'. Although some of Chinese nuclear institutes, companies and departments of universities have constructed their own networks and offered various nuclear information services, there is not any web-based numerical nuclear data service through the Internet (Worldwide Web, Telnet, and FTP) before 2001. Most of Chinese users and the public have limited success in accessing the nuclear data information service of international community. In order to change this situation, a new project was sponsored and funded in the beginning of 2001 by the Minister of Education of China. Its primary goal is to distribute international major nuclear data libraries via the Internet networks and to facilitate the visualization and manipulation of nuclear data by developing a web-based nuclear data services software system named as Nuclear Data Online Services (NDOS) at Peking University.

Using advanced relational databases and web-based information technologies, the NDOS system offers the online data services of a centralized repository of data including 8 major international nuclear data libraries for nuclear reaction data and for nuclear structure and decay data: 5 ENDF format evaluated databases (BROND-2.2, CENDL-2.1, ENDF/B-VI, JEF-2.2, and JENDL-3.3), ENSDF (Evaluated Nuclear Structure Data File) for nuclear structure and radioactive decay data, EXFOR (Exchange FORmat) for experimental data and the international photonuclear data files. The ENDF, ENSDF, EXFOR and photonuclear data files also introduce online data plotting capabilities.The version 1.0 of this software was tested and released in Sep. 2001, which only presented the comprehensive library of JENDL3.2 and the online plotting display of cross section data. In May 2002, the version 2 .0 was released and presented the full relational versions of five ENDF format evaluated neutron data libraries, the ENSDF library, the EXFOR library and the international photonuclear data library.

The computer programs providing support for database management and data retrievals are based on the Linux implementation of PHP and the MySQL software. PHP language is used for common software development, including programs for data loading and updating, as well as programs for access to the data through Web. The MySQL software, the SQL-compliant relational database management system (RDBMS) software, is the platform for nuclear data. The relational nuclear databases and data services are platform independent in a wide sense. The databases and main data services of the NDOS system resides on a PC workstation, which is maintained and hosted by the IHIP (Institute of Heavy Ion Physics) of Peking University, China. The most management functions of this system such as database adding, data loading and updating can be remotely implemented.

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## [14] Determination of gamma-ray emission probabilities and half-life of $^{101}$Mo

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The data of absolute emission probabilities of $^{101}$Mo were much different in some literatures, and its half-life was also inaccurate. In this paper, the gamma-ray emission probabilities of $^{101}$Mo have been measured with balance of scheme method using a vertical HPGe detector with a relative efficiency of 60%. The absolute emission probabilities of the main gamma-rays were determined from the absolute gamma-ray intensities and the disintegration rates, the results were 18.07±0.19% for 191.92keV, 20.39±0.43% for 590.10keV and 15.11±0.27% for 1012.47 keV, respectively. The $^{101}$Mo half-life was measured by relaying between two horizontal HPGe detector with a relative efficiency of 100% over a period of ∼10 half-lives. The result is 14.86±0.01 minutes.

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## [18] Improvements to the technique and measurement of delayed neutron yields in $^{232}$Th(p,f) and $^{238}$U(p,f), $^{238}$U(d,f) reactions

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There is described an improved technique for short-lived sources of delayed neutrons studying in compound $^{233,234,235}$Pa, $^{236-241}$Np nuclei fission at $^{232}$Th, $^{235,238}$U exposure to a pulsed beam of protons, deuterons and tritons at the tandem electrostatic accelerator EGP-10 [1]. To extend the measuring possibilities to the range of small decay times the electrostatic deflector electronics has been upgraded in order to decrease the current pulse edge to 10 mcsec. In the preliminary measurements at target irradiation the all-wave neutron counter channel was found to be overloaded with prompt fission neutrons and recovered rather slowly therewith. Therefore, the neutron counter electronics was substituted by the faster one, and the counter was calibrated on monoenergetic neutrons from $^{7}$Li(p,n) reaction. To identify individual beta decays of fission products by the life-times and provide reliable decomposition of the complex curve of delayed neutrons yield there has been introduced a channel with HPGe detector, which records gamma-ray energy and time distribution. Then there has been performed a series of measurements of absolute total yields of delayed neutrons from fission fragments in $^{232}$Th(p,f) and $^{238}$U(p,f), $^{238}$U(d,f) reactions with the projectile particle energies of 10–12 MeV. In the measurements samples of $^{232}$Th and $^{238}$U up to 7 mg/cm$^2$ thick were used applied onto 50 mu thick tantalum substrates. To monitor the number of fissions in the sample a semiconductor silicon detector of fission fragments was employed. The work was carried out under ISTC financial support (project #2253).

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## [25] Neutron-induced fission cross section of nuclei in the vicinity of $^{208}$Pb at energies below 60 MeV.

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Neutron induced fission of nuclei in the vicinity of lead is the subject of both applied and fundamental studies. The data on lead and bismuth are of interest for the feasibility studies of accelerator driven system, because the lead-bismuth eutectic is presently considered as an appropriate material for the neutron production target. In terms of fission process study, this region of the chart element is of

particular interest, because of possible manifestation of nuclear shell effects in the vicinity of the doubly magic nucleus $^{208}$Pb.

In work [1] the measurements of the neutron-induced fission cross sections of $^{205}$Tl, $^{204,206,207,208}$Pb and $^{209}$Bi have been carried out in the energy range up to 175 MeV. At incident neutron energies of several tens of MeV the cross sections are low enough to have a significant value. In the same time, the low-energy data are of special interest for fission theory, because an enhancement of quantum effects related with almost or completely filled (as for $^{208}$Pb) neutron and proton shells is expected as the excitation energy decreases.

In order to improve the data obtained in work [1] as well as to extend the incident energy range towards the low energies, we have measured the neutron-induced fission cross sections of the six above mentioned nuclides at neutron energies of 32.8; 45.3 and 59.9 MeV. The measurements were performed at the neutron beam facility of the Universite catholique de Louvain at Louvain-la-Neuve, Belgium. Quasi-monoenergetic neutron beams were produced by the $^{7}$Li(p,n) reaction. Fission fragments were detected with a multi-section Frisch-gridded ionization chamber (MFGIC) loaded with the sub-actinide targets under study and natural uranium target as a reference one. The fluence monitoring procedure was undertaken with the 59.9 MeV neutron beam and resulted in two measurements in agreement with each other derived from two different methods one using our MFGIC and our U target, the other using a fission chamber monitor previously calibrated with the proton recoil detection technique.

References:

1. G. Tutin et al., contribution to this conference.

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## [39] Comparison of Experimental and Calculated Mass Distributions of Fission Fragments in Proton-Induced Fission of $^{232}$Th, $^{235}$U, $^{238}$U and $^{237}$Np in the Intermediate Energy Region.

Oleg I. Batenkov[1], Vilen P. Eismont[1], Mikhail I. Majorov[1], Andrey N. Smirnov[1], Kjell Aleklett[2], Walter Loveland[3], Jan Blomgren[4], Henri Condé[4], Marieke C. Duijvestijn[5], Arjan J. Koning[5]

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Mass distributions of fragments produced by proton-induced fission of $^{232}$Th, $^{235}$U, $^{238}$U and $^{237}$Np at the proton energies 50 and 96 MeV are presented. The measurements were carried out at The Svedberg Laboratory, Uppsala, Sweden, with the use of a high-precision spectrometer for fission fragments and fission neutrons [1]. The spectrometer includes a scattering chamber containing the targets and six detector telescopes. Each telescope arm consists of two thin $Al_2O_3$ foils, two microchannel plates (MCP), and a surface barrier detector (SBD). The telescope arms were adjusted to be perpendicular to the direction of the moving compound nucleus centre-of-mass system, so as to compensate for the momentum transferred to the compound nucleus by the impinging projectile. Successive pulses from the two MCPs gave the fragment flight time over a variable flight path. The directions of the fission fragments were also obtained with the MCPs, while the fragment kinetic energies were determined using the SBDs, or in some cases by using the TOF information from the MCPs.

In addition, energy distributions of neutrons emitted at different angles with respect to the fragment emission directions were measured. This has allowed to obtain an important for a comparison with the theory [2] information about number and average energy of pre-fission (pre-equilibrium and equilibrium) and post-fission (emitted from totally accelerated fragments) neutrons.

The fission of $^{237}$Np is of particular interest, because the composite and intermediate nuclei formed as a result of the direct processes have high parameters of fissility ($Z^2/A$) and therefore major $\Gamma_f/\Gamma_n$, which results in short chains of fission chances, that is essential for a comparison with calculations.

The calculations were carried out in the framework of the TALYS code [3]. Results of such comparisons are discussed, as well as the possibilities to predict the outcome of the considerably more difficult measurements using neutron beams.

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## [40] On Nuclear Structure Effects in the Nucleon-Induced Fission Cross Sections of Nuclei Near $^{208}$Pb at Intermediate Energies

Vilen P. Eismont[1], Nikoaly P. Filatov[1], Andrey N. Smirnov[1], Gennady A. Tutin[1], Jan Blomgren[2], Henri Condé[2], Nils Olsson[3], Marieke C. Duijvestijn[4], Arjan J. Koning[4]

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The results of the fitting of the energy dependences of the neutron-induced fission cross sections of $^{205}$Tl, $^{204,206,207,208}$Pb and $^{209}$Bi measured in recent works [1,2] are given. There are indicitations that the fission cross section of $^{208}$Pb formed in the reaction $^{207}$Pb+n at excitation energies lower than 50 MeV (when the contribution of the emission fission is small, i.e., the compound nucleus gives the main contribution to fission) is lower than of $^{209}$Pb ($^{208}$Pb+n). At higher energies all the cross sections increase with the increase of the fissility parameter $Z^2/A$. Such a behaviour of the cross section of $^{208}$Pb is predicted by the computer code TALYS [3] as a consequence of the high (maximum for a lead isotope) barrier of the doubly magic nucleus.

The relaxation of shell effects with increasing of excitation energy is traced also by comparison of the dependences of the fission cross section ratios of various nuclei to the $^{209}$Bi fission cross section versus nucleon energy. For comparison, data on neutron-induced fission cross section ratios were taken from the papers [1,2] and data on both neutron- and proton-induced fission cross section ratios - from [4]. The experimental dependences are compared with theoretical ones calculated by TALYS. The degree of the agreement is discussed.

The problem of the role of nuclear deformation (the sphericity of nuclei having closed shells) in the competition of fission and neutron emission - a possibility that the stabilizing influence of a high barrier is compensated by destabilizing effects due to the low collective enrichment of the level density of spherical nuclei - was recently risen in connection with determination of the fission cross sections of Ra isotopes (near N=126) [5]. This issue is investigated by a comparison of the fission cross sections of lead isotopes with the ones of deformed nuclei.

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5 A Heinz, K.-H. Sabmiold, A. R. Funghous et al, GSI Preprint 2002-25 August.

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## [41] Angular Anisotropy of Intermediate Energy Nucleon-Induced Fission of Pb Isotopes and Bi

Vilen P. Eismont[1], Nikolay P. Filatov[1], Sergey N. Kirillov[1], Andrey N. Smirnov[1], Jan Blomgren[2], Henri Condé[2], Nils Olsson[3], Marieke C. Duijvestijn[4], Arjan J. Koning[4]

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The results of the measurements of the coefficients of anisotropy of proton-induced fission of $^{204,206,207,208}$Pb and $^{209}$Bi at the proton energies 48, 98 and 177 MeV are presented. The measurements have been carried out at The Svedberg Laboratory, Uppsala, Sweden, with the use of thin-film breakdown counters [1].

Data for $^{204}$Pb are obtained for the first time. The others supplement essentially the results of other work in this energy region. The dependence of the coefficients of anisotropy on proton energy is estimated in the frame of the standard statistical model [2,3] taking into account characteristics of interim compound nuclei formed in the process of the interaction of protons with lead and bismuth nuclei. The latter are calculated in the frame of the code TALYS [4], for which a comparison with experimental values of anisotropy is a new form of testing and verification.

It is concluded that the calculated results agree with the experiment. The values of the coefficients of anisotropy for $^{204}$Pb and $^{207}$Pb are calculated in the proton energy region 25 - 50 MeV where experimental

data are absent. In addition, the values of the coefficients of anisotropy for neutron-induced fission are predicted.

Special interest is indicated on measurement of the anisotropy of fission in reaction $^{207}$Pb(n,f) in the energy region of 20 - 40 MeV, where the contribution of first-chance fission exceeds 70% according to calculations by TALYS, i.e., the fission of the doubly magic nucleus $^{208}$Pb is playing an important role.

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## [42] Correlation of Intermediate Energy Proton- and Neutron-Induced Fission Cross Section in the Lead-Bismuth Region

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The recently published data on the intermediate energy proton- and neutron-induced fission cross sections of lead isotopes and neighbouring nuclei measured at The Svedberg Laboratory in Uppsala, Sweden [1] are supplemented with new experimental results. The fission cross sections are divided by the cross sections of the inelastic interaction of protons and neutrons with nuclei parameterized according to Barashenkov [2]. The average fissilities obtained as the result are considered from the point of view of their dependence on nucleon energy (at the energies above 50 MeV, when the shell effects do not play a significant role) and on the fissility parameter $Z^2/A$. Possible differences between contributions of direct processes (cascade and pre-equilibrium emission) and, therefore, of characteristics of interim compound nuclei for protons and neutrons are estimated with the use of the code TALYS [3]. Since the difference is found to be insignificant (within the frame of the present task), on this general physical base a relation between the intermediate energy proton- and neutron-induced fission cross sections in the region of A $\sim$ 200 is derived. The results of the work can be useful for both engineering calculations of neutron production target of ADS and examination of theoretical models.

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2. V. S. Barashenkov. "Cross sections of interactions of particles and nuclei with nuclei", Moscow, Atomizdat, 1972.
3. A.J. Koning, S. Hilaire, M.C. Duijvestijn, this conference.

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## [48] New Results from the Search for Neutrinoless Double Beta Decay with Enriched $^{76}$Ge in Gran Sasso

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The HEIDELBERG-MOSCOW Double-Beta-Decay experiment in GRAN SASSO has collected data in the period August 1990 - 2003. The measurement and the analysis of the data is presented. The collected statistics is 71.7 kg y. The background achieved in the energy region of the Q value for double beta decay is 0.11 events/kg y keV. The two-neutrino accompanied half-life is determined on the basis of more than 100 000 events. The confidence level for the neutrinoless signal has been improved.
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## [54] Mean angular momenta of primary photofission products

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Many problems still remain in fission process description, among which are interplay between nuclear structure effects and fission dynamic peculiarities in forming different fission characteristics, specifically of angular momenta distribution P(I) of primary fragments. One of the most simple and rather reliable method to deduce information on spin distribution P(I) (and hence on mean angular momenta <I>) is based on investigations of independent yield of isomer states with different spins (isomer ratios, $\sigma_m/\sigma_g$) in evaporation residues of primary fission products.

In this work isomer ratios and mean angular momenta for photofission products of $^{237}$Np and $^{238}$U are obtained. The method of gamma-ray spectrometry of fission products without radiochemical separation[1] are used with some modification for isomeric ratio determination. The nuclei are irradiated by microtron M-30 bremsstrahlung induced by electrons with energies 15 MeV and 16 MeV. Different irradiation and cooling time are used (1-120 min) to obtain optimal conditions for data acquisition. Gamma-ray spectra of photofission products are also analyzed at different time intervals to perform correct identification of the products. The contributions of genealogically related beta-decay branches are taken into account by solving of differential equation system of radioactive decay and growth in isobar chain of investigated nuclide.

As a result the following values of isomer ratios for photofission products are determined:
$^{237}$Np — $\sigma(8^-)/\sigma(4^+) = 2.4 \pm 0.2$ for $^{134}$I, $\sigma(11/2^-)/\sigma(3/2^+) = 0.61 \pm 0.06$ for $^{135}$Xe
$^{238}$U — $\sigma(8^-)/\sigma(4^+) = 1.2 \pm 0.2$ for $^{130}$Sb, $\sigma(8^-)/\sigma(4^+) = 0.79 \pm 0.13$ for $^{132}$Sb, $\sigma(11/2^-)/\sigma(3/2^+) = 0.032 \pm 0.015$ for $^{133}$Te, $\sigma(8^-)/\sigma(4^+) = 0.67 \pm 0.13$ for $^{134}$I and $\sigma(11.2^-)/\sigma(3/2+) = 0.22 \pm 0.03$ for $^{135}$Xe.

The modified version of EMPIRE-II code[2] is used to obtain spin distributions and mean angular momenta of primary photofission products. The preliminary results are in rather good agreement with that ones from [1], where values <I> were determined in fragments of $^{232}Th$ fission induced by 14 MeV neutrons.

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## [79] Status of the Neutron Cross Section Standards Database

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The International Atomic Energy Agency (IAEA) has commenced with a Co-ordinated Research Project (CRP) on improving the standard cross sections, with the focus on the light elements. This has to be seen in view of the upcoming new evaluation of the ENDF/B-VII. Since most neutron cross section measurements are made relative to neutron cross section standards, the standards evaluation is of crucial importance. The reactions contained in the standards data base are: H(n,n), $^{3}$He(n,p), $^{6}$Li(n,t), $^{10}$B(n,$\alpha$), $^{10}$B(n,$\alpha\gamma$), C(n,n) Au(n,$\gamma$) and $^{235}$U(n,f). Other reactions including the $^{238}$U(n,f) cross section were added to the NEANDC/INDC Nuclear Standards file. These standards received international acceptance to ensure that all evaluation projects use the same set of standards. The last complete evaluation of the standards file, however, dates back almost 20 years. In the meantime quite a number of new and improved measurements have occurred for the cross section standards. International efforts within the mentioned CRP are presently underway to update the experimental data base and to improve the evaluation process. Due to the need for high energy standards, the energy range is extended to 200 MeV for some of the cross section standards. The status of the work on this evaluation will be discussed.

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## [83] Prompt fission neutron emission in resonance fission of $^{239}$Pu

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The prompt fission neutron emission probability is being investigated at the time-of-flight facility GELINA at IRMM. A double Frisch-gridded ionization chamber is used as fission fragment detector. For the data acquisition of both the fission fragment signals as well as the neutron detector signals the fast digitization technique has been applied. For the neutron detection large volume liquid scintillation detectors from the DEMON collaboration are used. A specialized data analysis program taking advantage of the digital filtering technique has been developed to treat the acquired data.

Neutron multiplicity investigations for actinides, especially in resonance neutron induced fission, are rather scarce. They are, however, important for reactor control and safety issues as well as for understanding the basic physics of the fission process. Fission yield measurements on both $^{235}$U and $^{239}$Pu without prompt neutron emission coincidence have shown that fluctuation of the fission fragment mass distribution exists from resonance to resonance, larger in case of $^{235}$U. To be possibly able to explain these observations, the question is now, whether the prompt neutron multiplicity shows similar fluctuations with the resonance energy.

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## [88] EXPERIMENTAL INVESTIGATION AND CALCULATION OF ABSOLUTE EFFICIENCY OF $\gamma$-RAY DETECTION WITH HPGe-DETECTOR WITHIN 0.2 – 18.6 MEV ENERGY RANGE

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There have been performed experimental and calculation studies of absolute efficiency of $\gamma$-ray detection with GC 5019 HPGe-detector (CANBERRA). The work was carried out in connection and simultaneously with the differential cross sections (by angle) measurement of reactions of proton radiation capture on lightest nuclei ($^{9}$Be, $^{11}$B, $^{16}$O), conducted at the tandem electrostatic ion accelerator EGP-10. In the interval $E_{\gamma}$=0.2–3.56 MeV to perform the experiments the $^{137}$ Cs, $^{152}$Eu, $^{228}$Th reference

gamma sources were employed along with the $^{56}$Co source, produced at the accelerator's proton beam through $^{56}$Fe(p,n) $^{56}$Co reaction. Higher these energies $\gamma$-rays were used from the resonance reaction $^{27}$Al(p,$\gamma_2$)$^{28}$Si$^*$ (4.617 MeV) at $E_p$=2.489 MeV and $^{11}$B(p,$\gamma_1$) $^{12}$C$^*$ (4.439 MeV) and $^{11}$B(p,$\gamma_{11}$) $^{12}$C$^*$ (15.11 MeV) reactions at $E_p$ =2.54 and 2.091 MeV, respectively. The $\gamma$-ray sources were positioned at a distance of 127 mm from the detector crystal face surface. Before the detector a protective lead screen 5 mm thick was placed, and the detector itself was surrounded with a cylindrical lead protection, also 5 mm thick. To implement Monte Carlo simulations (by MCNP code) the detector crystal effective volume was determined, in which $\gamma$-ray were registered. It appeared on 10 % less than geometrical volume, as was the basis for introduction on all surface of a crystal of the dead layer equal 1 mm. With a certain indeterminancy of the data on the detector's core size taken into account, the obtained ratio, 1.05–1.07, of the calculated and experimental values of $\gamma$-ray detection efficiency in the full-energy peak can be considered as quite satisfactory. Physical processes are discussed that define $\gamma$-ray detection efficiency energy dependence.

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## [96] Thermal neutron cross section measurements for the $^{209}$Bi(n, $\gamma$)$^{210m}$Bi and $^{209}$Bi(n, $\gamma$)$^{210g}$Bi at the Budapest PGAA-NIPS facility

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The $^{209}$Bi(n,$\gamma$)$^{210m}$Bi and $^{209}$Bi(n,$\gamma$)$^{210g}$Bi cross-sections are important nuclear data, for the operation of Accelerator Driven Systems and long-term disposal aspects. These two reactions contribute significantly to the short- and long-term radiotoxicity of the spallation target via the production of $^{210}$Po ($T_{1/2}$ = 138.376 d) and $^{210m}$Bi ($T_{1/2}$ = 3.04$\times$10$^6$ y), both alpha-emitters. Since experimental data are very scarce, additional measurements are required. The IRMM and CEA Saclay started a collaboration to determine the cross sections and corresponding branching ratio in an energy region between thermal and 500 keV. To cover such an energy region measurements at a reactor beam and at GELINA are scheduled. The first experimental results at thermal energy were obtained at the ILL in 2002. The results deviate by about 25 % from the most recent evaluated data. To confirm the data obtained at the ILL, measurements at the cold neutron PGAA-NIPS facility, Budapest Neutron Centre were performed and will be reported.

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## [100] Sample dependent weighting functions and neutron sensitivity corrections for $C_6D_6$ detectors by Monte Carlo simulations

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To determine capture cross sections using $C_6D_6$ detectors, the Pulse Height Weighting Technique (PHWT) is mostly applied. Therefore, the quality of the data depends strongly on the detector response used for the calculation of the weighting function. In addition, for nuclei with small capture-to-scattering ratios (light and neutron magic nuclei) reliable capture cross section can only be obtained after a correction for the neutron sensitivity of the detector. An experimental determination of both the response and neutron sensitivity of $C_6D_6$ detectors is not always straightforward. We determined these quantities from Monte Carlo simulations, using the MCNP 4C3 code. To obtain reliable results a big effort was made in preparing a geometry input file describing the experimental conditions. To validate the results of the Monte Carlo simulations we performed several experiments at GELINA. We determined the neutron width of the 1.15 keV resonance in $^{56}$Fe using different sample compositions; we measured the $C_6D_6$ detector response for selected resonances in the $^{206}$Pb(n,$\gamma$) and for neutron scattering on $^{208}$Pb and on a carbon scatterer. The good agreement between experimental and simulated data confirms the reliability of the Monte Carlo simulations. Monte Carlo simulations can be used to determine weighting functions,

which also account for the photon transport in the sample. Such weighting functions are required for capture reactions in nuclei where the gamma cascade differs strongly from resonance to resonance, and are extremely important for neutron data related to reactor technologies where Pb-isotopes play an important role.

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## [118] Search for three-body force effects in neutron-deuteron scattering at 95 MeV

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Three-nucleon (3N) forces as they are understood today should have a measurable effect on the minimum of the angular distribution in elastic nucleon-deuteron scattering at intermediate energies. Neutron-deuteron (nd) elastic scattering is a more reliable test than proton-deuteron scattering because the absence of Coulomb effects allows a less ambiguous interpretation of the results. The nd scattering differential cross section at 95 MeV has been measured with the Medley experimental setup, using the neutron beam line of The Svedberg Laboratory, Uppsala. Recoil deuterons from a thin $CD_2$ target have been counted by telescopes at various angles, allowing a full angular distribution coverage. The neutron-proton differential cross section has also been determined and used for the absolute normalization. The results are compared with calculations of nucleon-nucleon interactions and can be perfectly described if 3N forces are included.

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## [174] Nuclear Reaction Cross Section Measurements Via Characterisation Of Soft Radiation Emitting Products

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Nuclear reaction cross section measurements via the activation technique are generally done using high-resolution $\gamma$-ray spectrometry. However, in cases where the radioactive product decays exclusively by EC (without emitting a $\gamma$-ray) resort has to be made to the rather subtle technique of X-ray spectrometry. Similarly for characterisation of pure $\beta^-$ emitters, gas flow proportional or liquid scintillation counting is applied. For both X-ray spectrometry and gas flow proportional counting thin solid samples are needed. For liquid scintillation counting, on the other hand, the disturbing organic and inorganic material has to be absent. Thus the use of radiochemical methods is most essential.

We studied the $^{nat}$Ti(p,xn)$^{49}$V ($T_{1/2}$ = 330 d) and $^{85}$Rb(p,xn)$^{82}$Sr ($T_{1/2}$ = 25.5 d) reactions from their respective thresholds up to 70 MeV via X-ray spectrometry. In each case a very clean radiochemical separation was performed and a thin source was prepared. The radioactivity of $^{49}$V was determined using the soft 4.5 keV $k_\alpha$ X-rays and that of $^{82}$Sr via the 13.4 keV $k_\alpha$ X-rays. In another study, the reactions $^{nat}$Ti(p,x)$^{45}$Ca ($T_{1/2}$ = 163 d), $^{89}$Y(n,p)$^{89}$Sr ($T_{1/2}$ = 50.5 d) and $^{nat}$Pb(p,x)$^{204}$Tl ($T_{1/2}$ = 3.78 a) were investigated. All the products are pure $\beta^-$ emitters and therefore clean radiochemical separations were mandatory. The radioactivity of $^{45}$Ca was determined by liquid scintillation counting and those of $^{89}$Sr and $^{204}$Tl via low-level anticoincidence $\beta^-$ counting.

In the presentation, the difficulties, pitfalls but also the advantages of the interdisciplinary techniques used will be discussed. The cross section data for $^{82}$Sr and $^{89}$Sr are of medical interest, those for $^{45}$Ca, $^{49}$V and $^{204}$Tl are of value for estimating the activation of irradiated materials.

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## [179] Neutrons for Science (NFS) at SPIRAL-2

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A huge number of high energy neutrons (in the range between 1 and 40 MeV), produced in the carbon converter via C(d,xn) reaction, will be available at the SPIRAL-2 project at GANIL (Caen, France) aiming to produce neutron-rich fission fragments. The facility is expected to be operational by 2009. The main goal of this study is to provide quantitative estimates on the possibility of using a 40 MeV (5mA; 200kW) linear deuteron accelerator in a combination with the rotating target-converter, as initially projected at SPIRAL-2 for RIB production, for other purposes, namely, a) material irradiations very close to the target-converter and b) time-of-flight (ToF) measurements with a pulsed neutron beams. This work is also aimed to give a direct comparison a) with the ITER and IFMIF irradiation environment in terms of available neutron fluxes, energy spectra, material damage rates, useful irradiation volumes, etc., b) with the existing ToF facilities as GELINA at Geel and n-ToF at CERN in terms of available neutron beam characteristics (flux intensities, neutron energy range, neutron energy resolution, signal-to-noise ratio, etc.).

As long as material irradiations are concerned, we show that the SPIRAL2 facility would in principle be able to provide quite comparable neutron flux density, energy spectra and irradiation temperature conditions as ITER. On the other hand, in comparison with IFMIF, SPIRAL-2 would deliver neutron fluxes and damage rates by a factor of 10-20 lower. In addition, much smaller sample volumes (by a factor of 50) would be useful. Typical numbers for SPIRAL-2 are as follows: with neutron flux higher than $5x10^{13}$ n $s^{-1}$ $cm^{-2}$ and material damage rates greater than 3 dpa/fpy we obtain 10 $cm^3$ of a useful irradiation volume. It is important to emphasise that a variable temperature environment (between 500°C and 1000°C or higher) for irradiations would be possible at SPIRAL-2.

In the case of ToF measurements with a pulsed neutron beams, we conclude that a dedicated pulsed neutron beam facility can be easily built using the deuteron beam, and consequently neutrons produced at 0°, as delivered by SPIRAL-2. An integrated neutron flux greater by a factor of 100 -1000 (if compared to n-ToF at CERN) in the energy range from 5 to 40 MeV and with the energy measurement resolution of 1%, could be reached. In addition, this ToF facility in principle could function in parallel to the RIB production factory. However, additional investigations to define the neutron beam limits in terms of signal-to-noise ratio including safety radiation are necessary to determine the size of the experimental hall, the thickness and composition of the shielding walls, ToF channel geometry and materials, etc. This work is still in progress.

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## [212] WWR-M REACTOR NEUTRON SPECTRUM STUDY AT 3 - 25 MEV BY DIFFERENTIAL PROTON RECOIL METHOD

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The fast part of the WWR-M reactor spectrum (fuel enrichment 36% of U-235) practically coincides with neutron spectrum from the U-235 thermal fission. Its research may allow
a) to test a theoretical conceptions of neutron emission at fission,
b) to search an abnormal energy-release at the heavy nuclei fission,
c) to consider high threshold neutron reactions in the chains of accumulation of radioactive nuclides such as U-232 and Pu-236 which complicate the fuel cycle radiation conditions.

To clarify both the reactor spectrum fast part shape and a question of the neutron excess in fission spectrum above 15 MeV, the spectrum of neutrons from the WWR-M reactor horizontal channel was studied. The differential proton recoil method at the angles of scattering 30, 35, 40, 45, 50, 55 degrees was applied. The spectra measured at the angles of 35, 40, 45, 50 degrees overlapped the energy interval 6 - 18 MeV. Measurements at the angle of 30 degree allowed to study the spectrum from 3 to 12 MeV and at the angle of 55 degree - from 8 to 25 MeV. At reconstruction of the neutron spectra braking protons in the polyethylene radiator, the energy dependence of (n,p) scattering cross section, and anisotropy of scattering above 12 MeV were taken into account. The neutron spectra were approximated by Maxwellian distribution E = E**(1/2) exp(-a0 E) whence "statistical" error of the parameter alpha (a0) was determined. This method allows to investigate a shape of the neutron energy spectrum above 15 MeV with an error about +- 10 %; in this case practically all uncertainty is connected with the angular dispersion of the outgoing protons.

It was carried out 5 series of the measurements. In the energy interval 3-12 MeV in most cases the values of parameter alpha lie in the range 0.609 -0.750. For the case of loading "fresh" fuel elements (in vicinity of our horizontal channel) the measured neutron spectrum is in a good agreement with U-235 fission spectrum and has parameters: a0 = (0.750 ± 0.010) 1/MeV, temperature T = (1.334±0.018) MeV, average energy E = (2.000±0.027) MeV. The analysis high energy range (above 15 MeV) for the measured spectra points to more hard character spectrum (average energy 3 - 5 MeV).

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## [217] Time Decay Constants of Resistive Detectors

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One of the biggest constraints in the operation of resistive detectors is the drop of their efficiency with the counting rate, attributed to the decrease of the charge gain. In order to clarify the origin of this problem, we carried out measurements of time variation of the charge pulse height from resistive detectors, operating in proportional regime, under high irradiation rates. The dynamic behaviour of these detectors was investigated through the determination of their time decay constants related to a stationary condition, where the charge gain becomes constant. To perform this study, a data acquisition system, which allows the users to observe in real-time the temporal variation of the energy spectrum, was specially designed.

A glass cylindrical proportional counter, filled with Ar + 10% $CH_4$ gas mixture at atmospheric pressure, was used to investigated the relaxation mechanisms associated with the resistive electrode. Measurements of the charge gains of these detectors, irradiated with different counting rates by 22 keV X-rays from a $^{109}$Cd source, were carried out utilizing a conventional charge amplifier electronic system and a NIM ADC (ND582).

The first successfully results on the fitting of the peak centroid position as a function of time, obtained for rates range from 220Hz up to 1230Hz, showed it can be described by a sum of two exponentials plus a constant term, probably due to the complexity of the glass delayed polarization processes. The time decay constants extracted from these data decrease with increasing rates, what is in accordance with previous results. Furthermore, we also observed, for a fixed counting rate, an exponential decrease of the FWHM photopeak as a function of time. For this same condition, the area under the peak diminishes slightly as a consequence of the detector gain lowering. The physical interpretation of these results is under way.

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## [232] An investigation of $^{154}$Eu as a high-precision multi-$\gamma$-ray intensity calibration standard for detector arrays.

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The decay of $^{154}$Eu has been studied using $\gamma$-ray singles and $\gamma - \gamma$ coincidence spectroscopy with an array of Compton-suppressed Ge detectors. Particular attention to coincidence summing in the analysis, with consideration of detailed decay cascades and angular correlation effects, suggests that previous studies have overlooked necessary corrections. It is concluded that $^{154}$Eu provides 26 $\gamma$-rays that can be used for relative efficiency calibrations from 120 to 1600 keV at the 0.7% precision level and that this precision could be improved in the future.

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## [251] Development of charged-particle emission DDX spectrometer with SSD telescope and pencil-beam DT neutron source

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Charged particle emission DDX is quite crucial physical quantity for fusion reactor development. At present, the measurement can be carried out by various methods based on a variety of detection techniques. However, generally speaking, the accuracy is not so good because the measurement possesses hard conditions of high background, low cross section and thus bad S/N ratio. In the present study, a telescope system with two SSDs of $\Delta$E and E was developed, and to catch the target particle the discrimination of measured particles was conducted from two-dimensional contour of the two detectors. The important point of the present spectrometer is utilization of the pencil-beam DT neutron source of FNS of JAERI. Under the abovementioned experimental conditions, the background level is kept to be quite low and a high S/N ratio can be expected, even if the telescope is arranged very close to the measuring sample. Also normally the measurable lower energy limit is around several MeV for alpha particle. But, in the present telescope spectrometer the lower measurable energy below 1 MeV was successfully achieved by employing the anticoincidence alpha spectrum of E and $\Delta$E detectors as the spectrum below the energy range of the standard limit of several MeV. This is because (1) the thickness of delta-E detector is thin and thus the energy loss of proton in the detector is suppressed up to about several hundreds keV, and (2) the background alpha particle in case of sample-out measurement is exceptionally low. The validity of the spectrometer has been confirmed through the experiment with an aluminum sample. Recently the measurement of beryllium, which is regarded as one of the most important materials in fusion reactor, has been performed. The preliminary result of it is to be described in the Conference.

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## [261] Development of Gas Proportional Scintillation Counter for light heavy ion detection

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In resent years, nuclear data are needed in medical field. Nuclear data for light heavy ion induced are especially needed in high precision for cancer treatment. Though the nuclear data are not accumulated enough to apply. We have a plan to measure light heavy ion nuclear data with a dE-E detector. Low density is needed to the dE detector, and we have two options for the dE detector, semiconductor detector (SSD) or Gas Counter. On one hand, SSD has a good energy resolution, but on the other hand, it is expensive and its decay time is on 100-microsecond order. Gas Counter is inexpensive, and Gas Proportional Scintillation Counter (GPSC) has fast decay time. Then, we developed a GPSC for dE detector, and its evaluation experiment was carried out in HIMAC (Heavy Ion Medical Accelerator in Chiba). We will report the results of the experiment, the performance of GPSC.

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## [274] Secondary charged particle measurement from 2 GeV electron induced reactions with current time of flight technique

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The yield and energy spectrum of secondary neutrons from high energy electron induced reactions are important to evaluate shielding design of high energy electron accelerator such as 4th generation

synchrotron light source. We measured the energy spectrum of secondary charged particles from C, Al, Cu and W plate bombarded with 2 GeV electrons at the injector Linac in Pohang Light Source, POSTECH, Korea. The charged particles are easy to distinguish from intense backgrounds, photons and neutrons, associated with the reaction by using coincidence and ΔE-E method. The charged particle data are useful to evaluate neutron data which are important to shielding design of accelerators.

Electrons of 2.04 GeV, 10Hz repetition rate, 1 ns width bombard a thin plate sample in front of beam dump inside the injector Linac tunnel. The sample set to incline 45 degree from the electron beam axis to decrease energy loss of emitted charged particles. Above the sample, at 90 degree from the electron beam axis, there is 10.4 m flight path with 3 m thick concrete collimater to lead secondary particles to detectors. The detector is a counter telescope consisted of two thin NE102A plastic scintillator and one thick Pilot-U scintillator. In this setup, high intensity photons and plural numbers of neutron and charged particle enter to the detector for each electron beam bunch. Thus, the detectors are connected to the electronics with Multi-hit TDC to measure time-of-flight of each particle. In addition, digital storage oscilloscope is also connected to the detector to take waveforms for 500 ns in 0.5 ns steps after electron beam signal. The energy spectrum of protons and deuterons for each samples were obtained from 50 MeV to 300 MeV and from 60 MeV to 250 MeV, respectively.

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## [284] Measurement of the average multiplicity of prompt-fission-neutrons from $^{238}$U(n,f) and $^{235}$U(n,f) from 0.7 to 200 MeV

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The experiments were carried out at the Los Alamos Neutron Science Center with the FIGARO setup installed on WNR, a "white" spallation neutron source. Fission Neutron Spectra were measured with a fission chamber (target) and liquid scintillators (fast neutron detectors with a lower threshold of 0.65 MeV and an upper threshold of 7.5 MeV). A refined analysis of the recently published FNS [1], was performed to extract the relative prompt-fission-neutron average multiplicity (nubar). The results, normalized to Frehaut data [2] at low energy, compare well to reference data up to 28 MeV and a recent evaluation performed at Bruyeres-le-Chatel. We will discuss the shape and the anisotropy of nubar - as measured at side angles and energy cuts - at higher energy.

[1] Th. Ethvignot et al., Physics Letters B, Volume 575, Issues 3-4, 27 November 2003, Pages 221-228
[2] J. Frehaut, private communication, EXFOR data (1976).

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## [285] The new Uppsala Neutron Beam Facility

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A new quasi-monoenergetic neutron-beam facility has been constructed at the The Svedberg Laboratory (TSL) in Uppsala, Sweden. Key features include an energy range of 20 to 175 MeV, high fluxes and the possibility of large-area fields. Besides cross-section measurements, the new facility has been designed specifically to provide optimal conditions for testing of single-event effects in electronics and for dosimetry development.

Neutrons are produced by the $^{7}$Li(p,n)$^{7}$Be reaction, using a proton beam from the Gustaf Werner cyclotron. The distance from the neutron production target to the point where the beam enters the experimental area is 3 meters. For a proton beam energy of 98 MeV, a beam current of 5 mA and a Li target thickness of 8 mm, this will give a neutron fluence of about 5 x $10^5$ neutrons/(cm$^2$ s).

This is an increase by a factor of 7 when compared to the previous neutron-beam facility. A variable collimator system allows beam profiles of up to 30 cm in diameter at the beginning of the experimental hall corresponding to a flux of 3.5 x $10^8$ neutrons/s for the conditions mentioned above. Neutron fields of diameters up to about 1.5 meters can be obtained by sacrificing intensity. The proton beam current is about a factor of 12 lower at energies above 100 MeV when the cyclotron operates in FM mode. This leads to a lower neutron fluence, which, however, can be partly compensated by the use of neutron production targets with a thickness of up to 26 mm. Thus, even at the highest energy, neutron fluences of about $10^5$ neutrons/(cm$^2$ s) can be achieved. An additional irradiation position is provided at the distance of about 1.9 m from the lithium target. The position allows one to increase the neutron flux further by a factor of 2.5, at the expense of limited accessibility and size of irradiated objects. This position can be used parasitically with other experiments. Commissioning runs have been scheduled for early 2004 with the goal to measure the neutron energy spectrum, the shape of the neutron beam and in order to evaluate the background environment. First experiments have been scheduled for late spring 2004.

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## [297] High Resolution Gamma-Ray Spectroscopy at the Institut Laue-Langevin

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The 58 MW reactor of the Institut Laue-Langevin in Grenoble (France) is currently the most intense thermal neutron source in the world. The reactor forms the basis for a research program covering a wide variety of fields, supplying neutrons to a broad range of instruments. In the case of the two gamma-ray spectrometers operating at ILL, the gamma-rays emitted after neutron capture can be recorded with parts-per-million resolution. This is achieved by diffracting the gamma-rays with almost perfect Si or Ge crystals. Precise measurement of the respective Bragg angles and the crystal lattice spacing permits the determination of wavelengths or energies. The high resolving power of $\Delta E/E \sim 10^{-6}$ allows accurate determination of the energies of the emitted gamma-rays following the neutron capture, and therefore precise neutron binding energy measurements. This, in combination with precise atomic mass data, leads access to the Avogadro constant. Moreover, this extraordinary energy resolution allows measurements of tiny Doppler effects caused by the de-excitation processes of nuclei following neutron capture. Thereby atomic recoils can be induced by the subsequent emission of gamma-rays or in various beta decay scenarios by the emission of electrons and/or neutrinos. From the analysis of those Doppler broadened line profiles it is then possible to gather information on the lifetime of the nuclear state which is depopulated by the measured transition and on the slowing down process of the recoiling atoms, which is determined by the inter-atomic potential. Measured lifetimes provide a sensitive test of the validity of different theoretical description of the behavior of a nuclear system. An overview of the present experimental activity undergoing at the two ILL gamma-ray spectrometers will be given with emphasis on few selected examples.

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## [337] Coincidence measurement of residue, neutron and light charged particle in an spallation experiment

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Spallation reactions are important due to their applications in various fields such as astrophysics, neutron sources, accelerator driven systems and production of radioactive beams. To obtain a quantitative

understanding of the spallation mechanism large experimental efforts have been done during the last years at the GSI-FRS to study residual nuclei production. These data have led to the improvements of nuclear models but also raised new questions which appeared impossible to answer with inclusive experiments alone. This is why a more complete experiment, called SPALADIN, has been proposed which aims at measuring as exclusively as possible the final states of the spallation reaction. This experiment will be performed at GSI and will study the spallation reaction $^{56}$Fe+p in reverse kinematics at 1 GeV/A. beginning by a test on C+p reaction. The detection of the evaporation residues is performed with the ALADIN magnet and various detectors: An ionisation chamber for charge identification, a ring imaging Cerenkov (RICH) for the velocity, high resolution position detectors (drift chambers) for the reconstruction of the magnetic rigidity. The evaporated particles are detected with LAND (neutrons) and with the upgraded MUSIC III (light charged particles) associated with its TOF-wall hodoscope from the ALADIN collaboration. The detection of all the characteristics (type and energy) of the evaporation particles and of the heavy residue will permit to reconstruct the remnant prior to evaporation in mass, charge and excitation energy. It will then be possible to check if the modelisation of the first stage of the reaction is able to predict these characteristics. Furthermore it will allow to study the models describing the various decay modes of the primary residue as evaporation models or Fermi break-up mechanism for the lighter system.

We will present the experimental method including the resolutions and efficiencies of the various detectors. Preliminary data will also been shown.

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## [364] A low noise CsI detector array for the precision measurement of parity nonconservation in $\vec{n}+p \rightarrow d+\gamma$

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The NPDGamma collaboration has constructed an apparatus to measure with a small uncertainty the size of the pion-nucleon coupling constant in the parity non conserving pion exchange weak potential for N-N interactions. This coupling constant is directly proportional to the parity violating up-down asymmetry in the angular distribution of 2.2 MeV gamma rays with respect to the neutron spin direction in the reaction where polarized cold neutrons are captured by para-hydrogen. The asymmetry has a predicted size of $5 \times 10^{-8}$ and we will measure it to 30%. For this purpose,a low noise, current mode, CsI detector array has been constructed and tested. The beam commissioning of the detector will start in early 2004 in the new flight path 12 at the LANSCE spallation source. We will describe the detector and show test results.

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## [370] Measurement of the H(n,n)H Elastic Scattering Angular Distribution at $E_n = 15$ MeV

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We have undertaken an experiment to measure the relative differential cross section for neutron scattering from hydrogen at a neutron energy of 15 MeV, for center-of-mass scattering angles from 60 degrees to 180 degrees. A total of eleven E-$\Delta E$ telescopes are used to detect the scattered protons at laboratory angles of 0, ±12, ±24, ±36, ±48, and ±60 degrees. This experiment is intended to extend the earlier work performed by this group at 10 MeV.[1] In order to avoid possible dead time problems and amplifier summing noise, a unique approach to the data acquisition is based on eleven individual

data acquisition boards, one for each detector telescope, installed in separate personal computers, each running independently. In this way, no multiplexing of the detector signals is required, and the noise associated with the summing of the signals is eliminated. Also an additional acquisition board and personal computer are used for a neutron detector, with gamma ray discrimination, as a neutron monitor. A detailed description of the data acquisition system will be given, and results from a preliminary analysis of the data will be presented.

[1] N. Boukharouba, F. B. Bateman, C. E. Brient, A. D. Carlson, S. M. Grimes, R. C. Haight, T. N. Massey, and O. A. Wasson, Phys. Rev. C65, 014004 (2002).

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## [373] A Measurement of the Parity-Violating Gamma-Ray Asymmetry in the Neutron-Proton Capture

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The NPDGamma experiment, currently under construction at LANSCE, aims to study the parity-violating weak interaction between protons and neutrons in the $\vec{n}$+p→d+$\gamma$ reaction. For the experiment NPDGamma collaboration has built a new flight path 12 at LANSCE, where pulsed cold neutrons are delivered. Neutrons are polarized by a $^3$He spin filter, and captured in a liquid para-hydrogen target. The 2.2-MeV gamma rays resulting from the reaction are detected in an array of CsI detectors in current mode. The goal of the experiment is to measure the parity-violating directional gamma asymmetry $A_\gamma$ to an accuracy of 5x10$^{-9}$, which is approximately 10% of its predicted value. A result from the NPDGamma experiment will provide a theoretically clean measurement of the weak pion-nucleon coupling, thus resolving the long-standing controversy in nuclear physics over its value. Commissioning of the experiment starts in January 2004. In this talk an overview and current status of the experiment will be presented.

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## [376] Pulsed Cold Neutron Beam Performance on Flight Path 12 at LANSCE

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Flight path 12 at LANSCE has been assigned to fundamental nuclear physics experiments. The first experiment on this beamline is a measurement of parity-violating directional gamma-ray asymmetry in the $\vec{n}$+p→d+$\gamma$ reaction. For this experiment the NPDGamma collaboration has built a pulsed cold neutron beamline. The FP12 m=3 supermirror neutron guide views a upstream/back-scattering partially-coupled cold hydrogen moderator. In this talk, we will describe the beamline and report our results for moderator brightness and neutron pulse shape. Measurement is compared to model calculation.

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## [379] Establishment of a Computer Database Containing Nuclear and Decay Data of k0-NAA

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A computer database containing nuclear and decay data of about 125 nuclei interested in the reactor neutron activation analysis based-on the k0-standardization method (k0-NAA) has been presented. Each nuclide consists of data, e.g. element's name, radionuclide produced by reaction of the reactor neutrons, half-lives, Q0- resonance integral to activation cross-section ratio, - effective resonance energy, FCd- cadmium transmission factor, Eg- gamma-line energy and corresponding k0-factors, etc. The establishment of the computer database aims at automizing of data processing in the k0-NAA, i.e. nuclide identification, correction of reactor fast neutron reactions and of complex decay schemes (18 types), and calculation of elemental concentration as well as uncertainty and limit of detection. The TURBO-VISION environment has been chosen for managing the database since its user-friendly characteristic including windows and scroll-bar systems. The OOP (object-oriented programming) function has also been applied in order to link the database to other modules of a k0-NAA software. The application of the database in a general k0-NAA software developed at Dalat NRI will be demonstrated. The evaluation of analysis quality using the standard reference materials (SRM) has also been shown.

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## [389] Simulation of 4$\pi$ Ge-Spectrometer by GEANT4

Jun Goto[1], Masahiko Sugawara[2], Masumi Oshima[1], Toh Yosuke[1], Atsushi Kimura[1], Akihiko Osa[1], Mitsuo Koizumi[1], Motoharu Mizumoto[1], Toshiro Ohsaki[3], Masayuki Igashira[3], Hideo Harada[4], Yasuki Nagai[5]

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The neutron capture and fission cross-sections of minor actinides are required in designing innovative nuclear reactors. Those cross-section data are, however, not sufficient at present. Therefore, we have started a project of "Fundamental Research and development on Neutron Cross Sections for Innovative Reactors using Advanced Radiation Measurement Technology" since last year. This project consists of (1) development of advanced measurement technology, (2) acquirement of neutron cross-sections of minor actinides, and (3) development of neutron cross-section utilization system. As for (1), we will develop a 4$\pi$ Ge- spectrometer for the measurement of the capture cross-sections using a prompt gamma-ray spectroscopic method. The purpose of the present study is to estimate a performance of the 4$\pi$ Ge-spectrometer.

In this spectrometer, 30 Ge detectors completely cover the solid angle surrounding a sample, consisting of two cluster detectors and four clover ones: the cluster detector contains six Ge crystals and one 6-fold segmented Ge crystal, and the clover detector has four Ge crystals. Outside of the Ge detectors is covered by BGO anti-Compton shields.

We calculate energy deposit of gamma-ray in the 4$\pi$ Ge-spectrometer by GEANT4 which is a toolkit for simulating the passage of particles through matter. From the result of the calculation, absolute full energy efficiencies were deduced to be $\sim$25% for 1 MeV and $\sim$1% for 0.8-1.8-2.9 MeV cascade gamma-rays, respectively. In the conference, results of the simulation will be presented.

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## [397] Development of a Data Acquisition System for 4$\pi$ Ge-spectrometer

Atsushi Kimura[1], Yosuke Toh[1], Mitsuo Koizumi[1], Akihiko Osa[1], Jun Goto[1], Masumi Oshima[1], Masayuki Igashira[2]

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The aim of our study is the acquisition of neutron cross-section data for the minor actinides (such as $^{237}$Np, $^{241}$Am and $^{243}$Am) that are important for the development of innovative nuclear reactor technology. We develop a new advanced measurement technology for the acquirement of neutron cross-section data of the minor actinides. In this technology, we construct a $4\pi$ Ge-spectrometer utilizing a prompt gamma-ray spectroscopic method with multiple gamma-ray detection (gamma-gamma coincidence) method. This spectrometer consists of 30 Ge crystals and BGO anti-Compton shields. Normally, a data acquisition system for such a big Ge spectrometer consists of many NIM modules; it requires large space; in addition, its cost of this system becomes huge (more than 2 million dollars per one Ge detector channel). To overcome these problem, we developed a new data acquisition system for the $4\pi$ Ge-spectrometer with digital signal processing (DSP) techniques. This system consists of three Main ADC modules, which measure the energy of gamma rays with DSP technique, five Fast Timing modules and a Coincidence module to detect a coincidence condition and to measure timing data. The preamplifier outputs of the Ge detectors are directly put into the Main ADC modules and the Fast Timing Modules. The outputs of BGO anti-Compton detectors are only put into the Fast Timing Modules. All modules can be mounted a 19 inches VME sub-rack, the cost of this system is less than 2000 dollars per one Ge detector channel.

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## [405] Nuclear Data activities at n_TOF

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The main goal of the n_TOF-ND-ADS (n_TOF Nuclear Data for ADS) project is to produce, evaluate and disseminate high precision cross sections for the main isotopes relevant to the waste incineration and the ADS design i.e. capture and fission cross sections for minor actinides, capture cross sections for the main fission products, structural and coolant materials. The two experimental campaigns performed at n_TOF in 2002 and 2003 will be reviewed with emphasis on the most significative results, in particular on radioactive samples. The main achievements expected at the end of the project (end of 2004) will be presented altogether with some directions for future plans.

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## [406] NEW PROMPT GAMMA NEUTRON ACTIVATION ANALYSIS FACILITY AT DALAT REACTOR

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This paper describes the new Prompt Gamma Neutron Activation Analysis (PGNAA) facility and the current activities of nuclear reaction data and nuclear structure group at Dalat research reactor, Vietnam. A new PGNAA facility located at the horizontal channel No. 4 has been designed and is under construction to be changed for the old one. Neutron spectrum at the end of the channel, which near reactor core was determined, and was used as input data for Monte-Carlo simulation. The new facility consists of beam moderator and beam collimator, beam stopper and beam catcher, sample holder, detector shield and biological shield. A new gamma ray spectrometer was used to commute the old one. Some useful parameters of the new facility were determine. The first utilizations of the facility are determination of Ko-factors to use in Prompt Gamma Neutron Activation Analysis technique.

The work has been done under IAEA Project VIE0011-007-008J

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## [408] Realizing The Opportunities of Neutron Cross Section Measurements at RIA

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The Rare Isotope Accelerator will produce many isotopes at never before seen rates. This will allow for the first time measurements on isotopes very far from stability and new measurement opportunities for unstable nuclei near stability. In fact, the production rates are such that it should be possible to collect 10 micrograms of many isotopes with a half-life of 1 day or more. This ability to make targets of short-lived nuclei enables the possibility of making neutron cross-section measurements important to the astrophysics and the stockpile stewardship communities. But to fully realize this opportunity, the appropriate infrastructure must be included at the RIA facility. This includes isotope harvesting capabilities, radiochemical areas for processing collected material, and an intense, ?mono-energetic?, tunable neutron source. As such, we have been developing a design for neutron source facility to be included at the RIA site. This facility would produce neutrons via intense beams of deuterons and protons on a variety of targets. The facility would also include the necessary radiochemical facilities for target processing. These infrastructure needs will be discussed in addition to the methods that would be employed at RIA for measuring these neutron cross-sections.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 and Los Alamos National Laboratory under contract W-7405-ENG-36.

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## [412] Measurement of Neutron Decay Parameters – The abBA Experiment

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We are developing an experiment to measure the correlations $a$, $A$, and $B$, and the fierz interference term $b$ in neutron decay, with a precision of approximately $10^{-4}$. The experiment uses an electromagnetic spectrometer in combination with two large-area segmented silicon detectors to detect the proton and electron from the decay in coincidence, with $4\pi$ acceptance for both particles. For the neutron-polarization-dependent observables $A$ and $B$, precision neutron polarimetry is achieved through the combination of a pulsed neutron beam, under construction at the SNS, and a polarized $^3$He neutron polarizer. Measuring $a$ and $A$ in the same apparatus provides a redundant determination of $\lambda = g_A/g_V$. Uncertainty in $\lambda$ dominates the uncertainty of CKM unitarity tests.

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## [452] Search for anomalies in a cross-section of thermal neutrons interaction with titanium hydride

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In many of Physics Laboratories all over the world there has recently arisen an interest to experiments related to thermal neutrons interaction with hydrides and deuterides of transition metals. Namely, these are the experiments associated with abnormally large interaction cross-sections of thermal neutrons with hydrogen nuclei included as compounds to a molecule of for example titanium hydride. The developed by today theory of the considered phenomenon explains this property of the cross-section by the fact that at low energies of neutrons ($E_n < 1.0eV$) that are lower than the energy of hydrogen atoms coupling in metals the mechanism of neutrons interaction with hydrogen atoms changes. The peculiar results available today require careful testing, comprehension and, probably, new interpretation. Thus, there appeared the necessity of measuring full interaction cross-sections of low-energy neutrons and hydrogen atoms in coupled condition. The source of thermal neutrons put forward in the present paper is developed on the base of tandem electrostatic Van de Graaf accelerator EGP-10. Primary neutrons were generated

through bombarding a thick beryllium target with deuterons. The registration of thermal neutrons was performed with the aid of $^3$He-counter. In the paper there are described the following parameters: geometry of measurements, neutron source parameters, methods of producing a sample of titanium hydrides. The data on studying position of thermal neutrons maximum in a moderator and the data on neutron spectra depending on the direction of air channel aimed at radiation withdrawal are available as well. There are estimated the fluence of thermal neutrons falling on a detector as well as preliminary data on interaction cross-section of thermal neutrons with titanium hydride. At the first stage there was set up a task of determining full interaction cross-section of thermal neutrons with titanium hydride possessing different structure: in the form of small crystallites and in amorphous state. Additional data on the character of neutrons interaction with metal hydrides will be obtained at studying radiation capture cross-sections and spectra of gamma-quanta.

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## [453] Excitation of energy levels of fissile nucleus shape isomers in the doorway-state in reactions with neutrons and deuterons

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In measurements of fission neutrons yields in direction of fission fragments motion in (d,pf) reactions at certain excitation energies threshold neutrons were detected [1]. Comparison of this data on neutron yields in $^{233}$U(d,pfn) and $^{239}$Pu(d,pfn) [2] reactions with dependence of average number of fission neutrons $\nu_p(E_n)$ in $^{233}$U(n,f) reaction and dependence of nuclear fissionabilities in $^{235}$U(d,pf) and $^{239}$Pu(d,pf) reactions on the excitation energy made it possible to form more clear pictures of the process of nuclear fission in (d,pf) reaction. Thus, subbarrier fission resonances in reactions $^{233}$U(d,pf), $^{235}$U(d,pf) and $^{239}$Pu(d,pf) [3] are conditioned not by vibrational states, but resonance excitation of low rotational statesin the second well (shape isomer energy levels), that occurs at deuteron break-up in Coulomb nuclear field, and by interaction between a produced neutron and a primary nucleus in the doorway state.

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## [457] Investigations of the Space Parity Violation and Interference Effects in the Fragment Angular Distributions of $^{233}$U, $^{235}$U, and $^{239}$Pu Fission by Resonance Neutrons

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Investigations of the space parity nonconserving (PNC) asymmetry of $^{233}$U, $^{235}$U, and $^{239}$Pu fission fragment emission and parity conserving (PC) interference effects of left-right and forward-backward asymmetries were carried out on the neutron beams of the reactor IBR-30 over the range of neutron energies from 0.02 eV to about 100 eV. All experimental results obtained have been found to be in a good mutual accordance within the frames of modern theoretical conceptions about the mechanisms of PNC and PC effects forming in fission process induced by slow neutrons. In case of the P-even interference effects of asymmetry the evident mutual well-marked irregularities in their neutron energy dependencies up to about 100 eV were observed. It is connected with the interference of s, p-resonances at fission compound stage according to modern theory. As a remarkable result of the PNC effect measurements the resonance behavior of the PNC asymmetry coefficients in the low neutron energy region ($E_n < 2$ eV) was observed. Unfortunately, the statistical accuracy of the PNC effect measurements is not enough for

observation of these resonance effect in other cases of more high energies. Results of simultaneous analysis of all three asymmetry effects for all three nuclei are presented. The satisfactory combined description of the experimental points is received. As a result of theoretical evaluation of these data main parameters and the estimates of nuclear matrix elements of the weak interaction for some p-resonances in the low energy range were extracted.

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## [463] Cross section standards for neutron-induced gamma-ray production in the MeV energy range

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Several neutron-induced gamma-ray production cross sections have been suggested as "secondary" standards. Fe(n,$n_1$'$\gamma$) producing the 847-keV gamma ray from the first excited state of $^{56}$Fe, Cr(n,$n_1$'$\gamma$) 1434 keV, Al(n,n'$\gamma$) 3004 keV, and Si(n,n'$\gamma$) 1779 keV, have all been considered as possible standards for neutrons in the MeV energy range. However in two recent evaluations [1, 2] the $E_n$=14.5-MeV cross section for Fe(n,n'$\gamma$) differs by about 25%, even though both evaluations report accuracies of +/- 5 to 10%. While there are many more measurements on Fe than on Cr, the data sets for Cr show better agreement than is the case for Fe. We discuss some of the complications in measuring these cross sections accurately, and present recent work using the GEANIE high-resolution Ge detector array at the LANSCE/WNR broad-spectrum neutron source to make both absolute and relative measurements on Fe, Cr, V, Si and Al in the energy range from 1 MeV to over 50 MeV. Results and recommendations will be presented.

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## [477] Measurement of the Effective Cross Section of the $^{233}$Th$(n,\gamma)^{234}$Th Reaction Using the KUR

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The cross section value of the second half of the $^{232}$Th$(n,\gamma)^{233}$Th$(n,\gamma)^{234}$Th reactions is determined. Approximately 100 mg of solid thorium (IV) nitrate tetra-hydrate ($Th(NO_3)_4 \cdot 4H_2O$) was irradiated together with 0.1143% Au-Al and 0.483% Co-Al alloy foils, in order to monitor the Westcott thermal neutron flux and epithermal index, viz the strength of the epithermal $dE/E$ component relative to the density of neutrons including both thermal and epithermal neutrons, by the multiple-foil activation method using the Au$(n,\gamma)$ and Co$(n,\gamma)$ reactions. The irradiation was performed at 5000 kW for 5 h in the Kyoto University Reactor (KUR). More than 13 days after the irradiation, thorium was chemically purified. The gamma-ray spectra of the purified thorium were obtained using high-purity Ge detectors (HPGes) to determine the activity of $^{234}$Th. The amount of $^{232}$Th recovered after the chemical purification was determined by the activation method. Effective cross section of the $^{232}$Th$(n,\gamma)^{233}$Th reaction, which is necessary in the process of the determination of the $^{233}$Th$(n,\gamma)^{234}$Th cross section, was calculated using the evaluated cross section and resonance integral in Japanese evaluated nuclear data library (JENDL)-3.2. The effective cross section varies mainly according to the epithermal index and the effective cross section of the $^{232}$Th$(n,\gamma)^{233}$Th reaction. Therefore, although, the comparison of the effective cross sections cannot be made unconditionally, our results are slightly smaller than the widely used value.

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# [490] A NEW FACILITY FOR HIGH-ENERGY NEUTRON-INDUCED FISSION STUDIES

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A new facility is constructed for measurements of neutron-induced fission cross sections on an absolute scale, i.e. versus the *np* scattering cross section, which is adopted as the primary neutron standard. Angular distributions of fission fragments are being measured as well, that allows us to deduce data on fission anisotropy and transferred linear momentum, which are virtually unmeasured for high-energy neutron fission. The study is motivated by needs of neutron metrology, fission theory, and waste transmutation concepts.

The facility makes use of the Uppsala neutron beam produced via the $^{7}$Li(p,n) reaction in the 20–180 MeV energy region. Fission fragments are detected by Si surface barrier detectors in a circular geometry. In order to measure neutron flux, recoil protons from polyethylene layer backings are detected by telescopes consisting of Si detectors and CsI(Tl) scintillator crystals. Time-of-flight distribution of fission events is measured by parallel plate avalanche counters.

An advantage of the experiment is that the fission fragment detection and the neutron flux measurement via *np* scattering are performed simultaneously and at the same position in the beam, and therefore many sources of systematic errors cancel out. Further reduction of systematic errors is achieved due to "embedded" determination of the effective solid angle of the detectors by counting $\alpha$-particles from radioactive decay of target nuclei.

The performance of the facility is illustrated by preliminary data obtained for the $^{238}$U(n,f) reaction.

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# Poster D

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## [6] Simple functional forms for total and total reaction cross sections from nucleon-nucleus collisions.

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Total reaction cross sections have been predicted for nucleons scattering from nuclei ranging in mass from 6 to 238 and for projectile energies from just above noticeable giant resonance excitation to 300 MeV. So also have been the mass variations of those cross sections at selected energies when they have been calculated using coordinate space optical potentials formed by full folding effective two-nucleon ($NN$) interactions with one body density matrix elements (OBDME) of the nuclear ground states. Good comparisons with data result when effective $NN$ interactions defined by medium modification of free $NN$ $t$ matrices are used. Such has been also the case for angular as well as integral data for scattering of $^6$He from hydrogen when analyzed using inverse kinematics.

However there is a simple three parameter functional form that reproduces the partial wave total reaction cross section values determined from those optical potential calculations; a functional form that also maps the total scattering cross section partial wave elements. Adjusting the theoretical defined parameter values has enabled us to fit the actual measured data values from the scattering involving (15) nuclei spanning the mass range from $^9$Be to $^{238}$U and for proton energies 10 to 300 MeV. Likewise total cross sections for neutron scattering from various nuclei can be equally well reproduced. Of import is that the three parameter values vary smoothly with mass and energy.

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## [7] MCAS: A Multichannel Algebraic Scattering theory of low energy nucleon-nucleus reactions.

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Low energy cross sections from the collision of nucleons with light mass nuclei show sharp as well as broad resonances upon a smooth, energy dependent background. Those resonances may correlate to states in the discrete spectrum of the target. To interpret such scattering data then requires use of a complex coupled channel reaction theory. Such a theory has been developed and forms the MCAS, a Multi-Channel Algebraic Scattering theory. The prime information sought, the scattering matrices, are determined therefrom by matrix methods built using sturmian-state expansions of the relevant nucleon-nucleus potential matrix. The important ingredient found is the matrix form of the Green function for the scattering. The matrix structure of those Green functions not only facilitates extraction of the sub-threshold (compound nucleus) bound-state spin-parity values and energies but also readily gives the energies and widths of resonances in the scattering regime. Applications for both proton and neutron scattering will be presented.

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## [8] Nuclear Fusion Rate of the Muonic $T_3$ Molecule

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The ground state binding energy, size, and effective nuclear charge of the muonic $T_3$ molecule are calculated using Born-Oppenheimer adiabatic approximation [1,2]. The system possesses two minimun positions. A symmetric planar vibrational model between two minima is assumed and the approximated potential are calculated in this region. Moreover, nuclear fusion rate calculations of the short-life molecule is carried out due to the overlap integral of the resonance nuclear compound nucleus and the molecular wave functions. The molecular wave function, $\Psi_{mol}$, representing the motion of $^6Li^*$ and $t$ nuclei under the

influence of an effective attractive potential and strong Coulomb repulsion, in the unit of $\hbar = e^2 = c = 1$, is written using phenomenological idea so that at large distances the wave function, which describes the size of the molecule, decreases exponentially:

$$\Psi_{mol}(r) = N_{mol}\frac{F_0(\eta, r)}{r}e^{-kr} \tag{1}$$

where $k = 2m_t\mathcal{E}_\prime$ is the wave vector, and $N_{mol}$ is the normalization factor calculated due to the molecular size, and $F_0(\eta, r)$ is the regular Coulomb solution which its parameters are defined in the full text. The probability of nuclear fusion, $\mathcal{W} = 2\pi(|\mathcal{E}_\prime - E_{th}|)| < \Psi_{mol}|\Psi_{res} > |^2$, is obtained from the overlap between the molecular and resonance wave functions. The resonance state $\Psi_{res}(r)$ is simply chosen as an outgoing Coulomb s-wave:

$$\Psi_{res}(r) = N_{res}\frac{e^{i\eta \ln qr}}{r} \tag{2}$$

where $\eta = Z_{_{eff}}\frac{q}{k}$ being the Sommerfeld parameter (here the fine structure constant $\alpha$ is equal to 1 in a.u.), and $q = \sqrt{2m_t|\mathcal{E}_\prime - E_{th}|}$, respectively. $\mathcal{E}_\prime$ is called the relative outgoing energy which is computed, and $E_{th}$ is the threshold energy. Also $N_{res}$ is the normalization factor in the nuclear volume. To avoid to more complexity, we ignored the $\Omega$ dependency of the wave function. According to the above assumptions, the transition amplitude (after integrating analytically over r), is given by:

$$\mathcal{A} \;=\; 4\pi N_{mol}N_{res}\frac{e^{(-\pi\eta/2)}(\frac{q}{k})^{(i\eta)}\Gamma(2+i\eta)}{k^2\Gamma(1-i\eta)}\int_0^1 \frac{(\frac{1-t}{t})^{i\eta}}{[1-i(2t-1)]^{1\eta+2}}dt. \tag{3}$$

We expect that $\frac{q}{k}$ is close to 1 near threshold and hence $\eta \approx Z_{_{eff}}$. The Complex integrand is computed numerically [3]. Result for the $\eta = 2.8$ is equal to a complex number $0.3022i - 0.04153$. Finally, the probability of the nuclear fusion is calculated and our results as well as others are given in the full text.

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## [10] Cross Sections for Multistep Direct Emission in Nucleon-Induced Reactions

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The energy-weighted sum rules (EWSRs) and the folding integral of the Feshbach, Kerman and Koonin (FKK) theory, that provides the cross sections of the multistep direct (MSD) reaction, require as input well-defined collective, one-phonon and/or incoherent one-step particle-hole cross sections (1SD). Thus, the theory of FKK allows for only one-particle emission. However, in nucleon-induced reactions at incident energies higher than the particle binding energy the nucleus is likely to be excited to unbound particle-hole final states that require special attention. This is because the unbound particle gives rise to more complicated direct processes.

In order to take these processes into account the 1SD cross section is split into the $1SD_{bound}$ one to bound final states and the $1SD_{unbound}$ to unbound particle-hole final states. The $1SD_{bound}$ includes cross sections to collective vibrational as well as to bound particle-hole states, both satisfying the EWSRs. Only the $1SD_{bound}$ can be folded into the MSD cross sections of FKK. On the other hand, the unbound particle of the $1SD_{unbound}$ can either give rise to gradual absorption by undergoing damping into the quasi-bound states of the compound nucleus or escape the nucleus even after a few rescattering collisions, giving rise to a one-step or multistep two-particle emission. The former process dominates at lower energies and the latter above 40 MeV. Both processes go beyond the scope of FKK.

Using the non-normal DWBA matrix elements to describe the intermediate stages of the MSD reaction and allowing for all sequences of reaction stages that contribute to a MSD reaction, it is shown that the FKK MSD cross sections for one-particle emission together with the $1SD_{unbound}$ for the more complicated processes describe well the inclusive emission of nucleons in the incident energy range from 25 MeV to 120 MeV.

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## [11] Soft-Rotator Coupled Channels Global Optical Potential for A=24-122 Mass Region Nuclides up to 200 MeV Incident Nucleon Energies

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Coupled-channels optical model with coupling built on nuclear wave functions of the Soft-rotator nuclear Hamiltonian was used to analyze available experimental optical interaction data with A=24-62 mass nuclides. Necessary Soft-rotator nuclear Hamiltonian parameters of even-even nuclides in the mass region considered were found to describe observed low-lying collective levels as members of the G. S.; K=$2^+$; $n_{\beta_2}$=1, K=$0^+$ and K=$0^-$ negative parity bands. Search option of coupled-channels optical model code OPTMAN was used to find individual optical potential parameters allowing best fit of available experimental data both for neutrons and protons simultaneously. Potential used, considers dispersion relationship as proposed by Delaroche *et al.*, imaginary components equal zero at Fermi energies - property stemming from nuclear matter theory and high-energy saturation consistent with the Dirac phenomenology. Lane model with the Coulomb correction term proportional to the derivative of the rest real potential energy dependence was used to describe neutron-proton potential difference. We found, that all the available experimental optical data (s- and p-wave strength functions, scattering radius, total cross sections, angular distributions of elastically and inelastically scattered nucleons and reaction cross sections) for nuclides with A=24-62 can be described with good accuracy using optical potential with the smooth dependencies of potential values, radii and difusenesses (imaginary volume potential geometry is considered to be equal real potential one), while individual properties of the nuclides are accounted by individuality of the nuclear Hamiltonian parameters, Fermi energies and deformations.

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## [17] A Recent Development of the Dubna CASCADE Code

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The standard Dubna Monte Carlo code CASCADE1 for calculation of intra- and inter-nuclear cascades has been revised and improved. Various aspects of level density dependency on excitation energy of decaying post cascade nuclei and influence of shell corrections are studied. An improved library of hadron-nucleus and a more exact phenomenological approximation for nucleus-nucleus cross-sections are introduced. The cross-section library is used to calculate the probability of evaporation channels of excited compound nuclei. The pre-compound nucleus decay has been taken into account. The code is used to simulate irradiation of multi-component heterogeneous systems by high-energy particles, in particular, to study ADS for energy production and transmutation of nuclear waste.

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## [31] ACTINIDE SYMMETRIC/ASYMMETRIC NUCLEON-INDUCED FISSION UP TO 200 MeV

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The transition from asymmetric to symmetric (SL) fission in actinide neutron-induced fission is a long-standing problem of nuclear fission. Recently it was investigated experimentally for the $^{235}$U(n,f) reaction for $E_n \lesssim$250 MeV, as a function of the excitation energy [1] of fissioning nucleus prior to scission. In the emissive fission domain branching ratio of symmetric and asymmetric $^{238}$U neutron-induced fission modes $\sigma_{nf}^{sym}/(\sigma_{nf}^{sym}+\sigma_{nf}^{asym})$ was obtained by Zoller et al. [2] up to $E_n$ ~500 MeV. Below emissive fission threshold measured SL-mode fission cross sections of $^{235}$U(n,f), $^{238}$U(n,f) and $^{237}$Np(n,f) reactions up to the emissive fission threshold could be described within a Hauser-Feshbach statistical model. A separate rather high outer fission barrier with significant transparency was assumed for the SL-mode, while the inner one was assumed to be the same for the symmetric SL- and the asymmetric (S1+S2)-modes. Axial

asymmetry and mass-symmetry is assumed for the outer saddle of the SL-mode, as distinct from the S1- and S2-modes, for which saddles are axially symmetric and mass-asymmetric. With increase of the incident nucleon energy above emissive fission threshold and up to $E_n$ ~200 MeV about ~20 nuclides might contribute to the fission observables, however this number is dependent upon the target nuclide fissility, being lower for the higher fissilities. Observed neutron-induced fission cross sections of $^{238}$U target nuclide could be described in a fission/evaporation approximation up to $E_n$ ~200 MeV. To describe the ratio of the symmetric mode fission cross section $\sigma_{nf}^{symm}$ to all fission events for $^{238}$U(n,f) reaction [3] we assume that for $E_n \gtrsim$80 MeV neutron-deficient nuclei contribute mostly to the observed fission cross section. Observed fission cross sections of lower mass uranium target nuclides $^{235}$U, $^{233}$U are calculated based on the consistent description of branching ratio and observed fission cross section of $^{238}$U(n,f) reaction. Observed neutron-induced fission cross sections of $^{232}$Th, $^{237}$Np and $^{239,240,242,244}$Pu targets are described in fission/evaporation approximation up to $E_n$ ~200 MeV. Sensitivity of branching ratio to the target nuclide fissility is investigated also for the $^{232}$Th, $^{237}$Np and $^{239,240,242,244}$Pu target nuclides. The probability of symmetric fission in $^{235}$U(n,f) reaction for $E_n \lesssim$200 MeV [1] is investigated as a function of excitation energy of fissioning nucleus prior to scission, for that the partial (n,xnf) reaction neutron spectra are calculated within a Hauser-Feshbach statistical model. Symmetric/asymmetric mode partitioning of fission cross section is compared for the $^{238}$U(n,f) and $^{238}$U(p,f) reactions up to $E_{n(p)}$ ~200 MeV.

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### [44] Effective Inter-cluster Potentials and 3-cluster Faddeev Calculation of Nuclear Data


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Nuclear reactions among light nuclei, namely n, p, d, t, $^3$He and $^4$He, have been attracting strong attentions in nuclear physics as important and indispensable problems to understand dynamics of few-nucleon systems. For example, studies on three-nucleon systems have revealed a clear evidence of 3-body nuclear force which cannot be assessed by a study of nucleon(N)-nucleon interaction alone. Furthermore, treatment of structures and reactions involving 3 or 4 of them has been a big challenge in terms of Faddeev and Faddeev-Yakubovsky theories. The inter-cluster potentials between an urbitary combination of these light particles are input data crucially important for the studies of these few-cluster systems. Besides these basic interests, reactions among these nuclei are important for applications such as nuclear-astrophysics (nucleosynthesis, solar neutrino problem and so on) and nuclear energy fields.

In this work, we have systematically calculated inter-cluster potentials for light nuclei with the Resonating Group Method (RGM), and Pauli-forbidden states were eliminated in terms of the Orthogonally Condition Model (OCM) and finally the separable potentials in the momentum representation were generated by the Enrst Shakin Thaler (EST) expansion method or Generalized Separable Expansion (GSE).

The potentials we have generated are categolized as follows :

| | n | p | d | t | $^3$He | $^4$He |
|---|---|---|---|---|---|---|
| n | NN | NN | Faddeev | ◯ | ◯ | ◯ |
| p | | NN | Faddeev | ◯ | ◯ | ◯ |
| d | | | ◯ | ◯ | ◯ | ◯ |
| t | | | | ◯ | ◯ | ◯ |
| $^3$He | | | | | ◯ | ◯ |
| $^4$He | | | | | | ◯ |

where NN denotes that realistic nucleon-nucleon potentials (such as Paris or AV14) were used for combination of n and p, while Faddeev denotes that n-d and p-d potentials were obtained by a Faddeev calculation with realistic NN potentials as input data. All the other combinations marked by ◯ were generated by the RGM, OCM and EST/GSE method.

The potentials generated in this work serve as a database for sophisticated Faddeev or Faddeev-Yakubovsky studies. Reults of such calculations will be presented in this conference to show possibility of such an approach to generate nuclear data for light nuclei in a systematic way.

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## [51] Implantation and testing of photonuclear channel in code EMPIRE II

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Photonuclear reaction is one of the most important processes to study nuclear reaction mechanisms and to investigate giant multipole resonance properties.

In this work the improvements and extensions of the EMPIRE II code [1] are made to include the photonuclear channel. The code is also adapted to calculate isomer ratios, spin distributions and mean angular momenta of fission products. Different models for description of the dipole radiative strength function (RSF) are incorporated, namely, standard Lorentzian (SLO) [2], enhanced generalized Lorentzian (EGLO)[2,3], generalized Fermi liquid model (GFL) [2,4], modified Lorentzian approach (MLO) [2,5].

Photoabsorption cross-sections are calculated for medium and heavy nuclei. They are compared with experimental data to test both the RSF models and different sets of giant dipole resonance parameters.

The results of the calculations within all approaches are in close agreement in region of the giant dipole resonance. However they are rather distinct in energy regions far from photoabsorption peak. In particular, calculations within the EGLO model underestimate experimental values of photoabsorption cross-sections in the energy range close to neutron separation energy and the SLO model overestimate the data. Calculations within the GFL and MLO models provide good overall description of the photoabsorption cross-sections in the gamma-ray energy range till $\leq$20 MeV. They are recommended for theoretical estimation of the photoabsorption cross-sections in the middle and heavy nuclei.

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## [52] Dependence of E1 radiative strength function on neutron excess

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The radiative strength functions (RSF) are an important constituent to calculate capture cross sections, gamma-ray production spectra, isomeric state populations and competition between emission of

gamma-rays and particles. The expressions of dipole RSF in the approximation of an symmetric nucleus (with the same numbers of neutrons, $N$, and protons, $Z$) is used as a rule in practical calculations. This leads to an underestimate of a total width of the RSF as well as to a distortion of the RSF shape, specifically in the range of gamma-ray energies close to the neutron separation energy (the pygmy dipole resonance region).

In this work the electric dipole RSF of neutron-rich spherical nuclei is studied using semiclassical methods based on the solution of the Landau-Vlasov kinetic equation for finite two-component systems. In order to obtain accurate results in the pygmy dipole resonance region, it is vital to treat the centre of mass (c.m.) motion correctly. To study this problem the semiclassical RPA (kinetic-theory) approach including dynamical surface effects[1] is used. It is shown that the spurious c.m. motion is exact separated with the use of this method. The resulting isovector dipole RSF displays the low-energy resonance below the giant one. The calculations of the dipole response have been done also by using the semiclassical RPA approach[2] which is modified by an approximate prescription for the separation of the c.m. motion like that one used in the quantum RPA calculations[3]. The results of the both calculations are in rather good agreement. The latter semiclassical approach is used to make more sophisticated calculations with allowance for memory effects in the nucleon collisions[4].

It is found that the neutron excess leads to decrease the collectivity of the isovector giant dipole resonance due to a strengthening of the Landau damping. An additional low-energy strength appears at the values of the asymmetry parameter $I = (N - Z)/A$ like that one in nucleus $^{208}$Pb. The approach allows to improve the reliability of the dipole RSF in the wide range of energy from zero to the giant dipole resonance region.

This work is supported in part by the IAEA(Vienna) under IAEA Research Contract No.12492/R0/RBF.

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## [57] Monte Carlo simulations of the statistical decay of fission fragment in thermal n+$^{235}$U reaction and spontaneous fission of $^{252}$Cf

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Advanced Monte-Carlo simulations of the statistical decay of fission fragment have been implemented.

This approach provides new information regarding correlations in the neutron spectrum through the Los Alamos model. In particular, correlations between emitted neutron energies and multiplicities but also prompt neutron multiplicity distribution $P(\nu)$ (and not only the average prompt neutron multiplicity $\bar{\nu}$) and $\gamma$ ray spectra from fission fragments are obtained. We have first tackled the cases of thermal $n$+$^{235}$U and spontaneous fission in $^{252}$Cf including constraints on the available experimental data on $(E^*, J, A_L, A_H)$ distributions.

This kind of information is needed in simulations of detection of nuclear materials and will be utilized by a future upgraded version of MCNP.

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## [67] Angle Between Two Fission Fragments in Fission by Fast Protons

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The theoretical Monte-Carlo modeling is done of the fission fragments' relative emission angle in the fast proton fission reaction p+Th232. The results obtained are compared with the experimental data obtained from literature. The principal aim is to study the possibilities to use the experimental information on fission fragments angular distribution for testing the model codes used to describe nuclear reactions at these energies.

Dubna version of the cascade-evaporation model CEM [1] was used in the theoretical approach together with the additional block for the calculation of fission fragments' masses which used the experimental data [2]. Fragments emission angle is defined by the characteristics of all the reaction stages of the model as well as by the process of particle evaporation from the moving fission fragments. Possible fragments re-scattering in the target was also taken into account.

Experimental data were taken from two publications presenting the results of two experimental groups. The first group studied [3] fragments emission angles in p+Th232 reaction induced by protons with energies 140, 250 , 500 and 1000 MeV. The second group [4] studied fragments emission angles as a function of the emitted neutrons multiplicities in the reaction p+U238 at proton energy 475 MeV.

The comparison of the calculated results with the experiment leads to the following conclusions: The CEM code describes satisfactory both the dependence of the fragments emission angle on the incident particle energy and on the emitted neutron multiplicities. The experimental dispersions of the fragments' emission angles are larger than the theoretical ones. Detailed analysis suggests that the CEM code lacks the events with large momentum transfer to the target nucleus.

There are also reasons to believe that one should take into account additional channels of fast proton interaction with the target nucleus, which are not described in the framework of CEM code (probably direct reactions of (p,alpha) type). The present work is done to support the suggestion of measurements made [5] in the ISTC project ¹2604 .

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## [68] Correlation Between Charge Radii and p + Zr Reaction Cross sections for Zr isotopes with A = 90 -100

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Mean squared charge radii for a range of Zr isotopes have recently become available. When these values are plotted as a function of the mass number, they show an abrupt jump with a change of slope around mass A = 98. Relativistic mean field calculations have been performed to understand this feature. To further investigate this anomalous behaviour of mean squared charge radii, the proton elastic scattering data at 50 MeV available for the zirconium isotopes A = 90 -96 have been analysed by microscopic and phenomenological optical potentials. Predictions have been made for the elastic scattering cross sections for the isotopes with A = 98 and 100. The reaction cross sections obtained from the optical model analysis are plotted against mass number. There is a correlation between the charge radii and the corresponding reaction cross sections as a function of mass number of Zr isotopes in the region A = 90 -100.It is proposed to measure the proton elastic cross sections for these unstable Z isotopes to confirm this prediction.

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## [113] Optical model potentials for $\alpha$-particles scattering around the Coulomb barrier on medium-mass nuclei

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The double-folding formalism [1] of the $\alpha$-nucleus optical potential has been applied within a semi-microscopic analysis of the $\alpha$-particle elastic scattering on A$\sim$50 and A$\sim$140 nuclei at energies below 32 MeV, the first phase of the work was concerned with A$\sim$100 nuclei [2]. The energy-dependent phenomenological imaginary part for this semi-microscopic optical model potential (OMP) is obtained as well as the dispersive correction to the microscopic real potential. This imaginary potential is then introduced within a complete phenomenological analysis of the same data basis. A global or at least a regional parameter set of the phenomenological OMP for low-energy $\alpha$-particles has thus been obtained for medium-mass nuclei. This approach provides finally an optical potential parameter set easily used in further analyses or predictions to basic scattering problems in nuclear physics as well as in nuclear technology. It will be used and checked in the analysis of either the $\alpha$-induced or $(n, \alpha)$ reaction cross sections. These were not taken into account in this work to avoid the discussion of the remaining statistical model parameters (see, e.g., Ref. [3]), as well as the uncertainties in the parameters expected for the predictions for $\alpha$-particles emitted from excited compound residual nuclei [4]. Further work will concern the energies between 40 and 80 MeV, in order to complete the description already provided for higher energies [5].

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## [128] Spin dependent nuclear level density formulae using analytic number theory

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We compute the spin dependent nuclear level density for a set of nuclei at moderate excitation energies. Our method is an exact calculation using procedures of analytic number theory by consideration of the statistical partition functions in terms of elliptic functions. The basis is an arbitrary finite set of single particle energy levels around the Fermi level. To avoid edge effects, a periodic spectrum is constructed. Ground state as well as energy dependent shell effects are naturally included. The usual Gaussian angular momentum distribution is extended to an exact description for these spectra. This new description allows therefore the analytical calculation of additional terms beyond the well known relations. Also, a set of simple asymptotic formulae can be deduced from our results providing the next correction terms to the usual level density formulae. These new relations could be used to describe experimental data in simple terms. Comparisons with older methods will be presented showing their limitations. Our approach is based on a solid mathematical framework, instead of the standard phenomenologycal ad-hoc relations or of the lengthy brute force numerical methods.

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## [131] Nuclear Reaction Model Analysis of the Fast Neutron Induced (n,p) Reaction Cross Sections

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In last decade, a systematic study of known experimental cross sections of the (n,p) and (n,a) reactions induced by fast neutrons was carried out in the wide energy interval and for a broad mass numbers of target nuclei [1-3].

In this paper, we suggest a theoretical explanation on existence of a systematic regularity which was observed in the fast neutron induced (n,p) reaction cross sections. For the theoretical analysis the statistical model, simple exciton model of Griffin and PWBA are used. For systematic analysis of (n,p) reaction cross sections simple and convenient formulae were deduced. It was shown that theoretical (n,p) cross sections are satisfactorily in agreement with experimental values for the 14.5 MeV neutrons.

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## [158] Calculations of emission neutrons and fission fragment yields for intermediate energy nucleon-induced reactions

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The code system MCFx developed earlier [1] on the base of extended cascade-evaporation model for description of fission cross-sections was adapted to calculations of emission neutron and fission fragment yields in reactions on heavy nuclei induced by neutrons and protons of intermediate energies.

Model of fission fragment mass distribution originated from the properties of deformation energy surface near the scission point has been evolved and incorporated into the MCFx code. Calculations for $^{209}$Bi(p,x) and $^{238}$U(p,x) reactions in 100-500 MeV energy region have been carried out.

Results of fission fragment calculations are in good agreement with experimental data [2] as well as mean number and spectra of prefission neutrons emitted by a number of excited nuclei at the final stage of reaction. The agreement of averaged fission fragment mass indicates that nonequilibrium stage of reaction is described in the proper way (cascade and preequlibrium reaction stages).

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## [168] Fission yield predictions with TALYS

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The new nuclear model code TALYS [1] has been extended to enable the prediction of fission yields. Fission competition is taken into account throughout the whole evaporation chain. Subsequently, the fission fragment mass yields are computed per excitation energy bin for each fissioning residual nucleus in two steps:

- the relative contributions of the different fission modes are evaluated with the Hill-Wheeler penetrability through inverted parabolic barriers using ground-state level densities and temperature-dependent barrier parameters [2],
- the fission-fragment mass distributions corresponding to each fission mode are calculated in the framework of the multi-modal random-neck rupture model by Brosa et al. [1,2].

Finally, the charge yields of the fission fragment are determined using the scission-point model [4]. Both actinide and subactinide fission-fragment mass yields and isotopic yields are compared to experimental results.

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## [176] Fission Fragment Distributions and Delayed Neutron Yields

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Recently a renewed interest in photonuclear processes has appeared. It is motivated by a number of different applications where progress in compact, reliable and high intensity electron accelerators was awaited. Some of these applications as radioactive ion beam (RIB) production, non-destructive characterization of waste barrels and detection of nuclear materials require a good knowledge of fission fragment distributions from photon induced fission. For most of the actinides these distributions are well known for neutron-induced fission, what is not the case for photon-induced fission. A companion paper describes developments and testing of the new photonuclear activation data library for CINDER'90, which also needs fission fragment distributions from photo-fission.

In this work we use the GSI fission-evaporation code which is known to give good results for the spallation process, where during the de-excitation process the nucleus looses its energy via evaporation and/or fission. In the case of photo-fission, the physics model is divided into two parts: the input channel with the photon absorption and nucleus excitation, and the output channel, that is the nucleus de-excitation. The nucleus excitation by photon is based on the giant dipole and giant quadruple resonances. The absorption cross section is the sum of these components, each of them determined from empirical systematics. The nucleus de-excitation is achieved with an independent code based on a statistical model, where fission is in a direct competition with particle emission. In other words, the complete code provides neutron (proton) emission and fission cross sections, and also fission yields. Multi-chance fissions are also taken into account.

The goal of our study is twofold:
a) we test the validity of the GSI fission-evaporation codes to predict photo-fission fragment distributions and, consequently, to characterize the corresponding delayed neutron yields;
b) we try to establish some systematic relationship with neutron induced fission at similar excitation energies.

By comparing our predictions for the U-235, U-238, and Pu-239 nuclei to the corresponding experimental data and other model calculations or library evaluations we conclude that the GSI fission-evaporation model is a powerful tool to describe photo-fission fragment distributions. Consequently, delayed neutron calculations also agree rather well with existing experimental data. On the other hand, we found some discrepancies for the particle emission and fission cross sections even though the total photon-induced absorption cross sections were well reproduced. These discrepancies depend on the incident photon energy and on the target nucleus. We believe that the major reason is the difficulty to get the right competition between evaporation and fission. We also aimed in showing the systematic similarity between neutron and photon-induced fission, but from this preliminary study no clear conclusions can be drawn at the moment.

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## [187] Vibrational enhancement of nuclear level density within response function method

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The response function approach was proposed in Ref.[1] for calculation of vibrational enhancement of nuclear level density[2]. It allows to take into account the damping of vibrational states in a rather accurate way. Vibrational states are considered as collective states formed both by coherent interactions of a separable form and by non-coherent residual interaction for description of the damping.

In this contribution this method is modified and corrected. The variation of the partition function $\Delta Z$ due to collective vibration is calculated as the Matsubara sums[3] for collective response function. The nuclear response function is determined by the use of the Landau-Vlasov kinetic equation. Non-coherent residual interactions are included within relaxation time method with retardation effects during two-body collisions[4]. Ratio, $K$, of nuclear level densities with and without allowing for vibrational states is studied as a function of the excitation energy. The effect of the collective state damping both on factor $K$ and on nuclear temperature is considered. The results of the calculations demonstrates rather strong dependence of $K$ on a shape of the vibrational state damping width.

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## [194] THEORETICAL MODELS AND RELEVANT CALCULATIONS OF PHOTON PRODUCTION AND PHOTONUCLEAR REACTION DATA

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Photon production and photonuclear reaction data, with emphasis to theoretical model aspects aimed to reliable evaluations, represent a challenge in many technological applications, from radiation shielding for different nuclear, including accelerator, systems to devices relevant to nuclear energy applications, particularly the ones concerning the Accelerator Driven Systems for nuclear waste transmutation.

In fact, theoretical calculations complementing the existing experimental data, mainly when the measured quantities are discrepant, scarce or even lacking, play an essential role in performing valuable nuclear data evaluations in this field of applied science. In this framework, new improved results of theoretical and evaluation activities carried out at ENEA, Division for Advanced Physics Technologies, are presented, especially concerning photon production data, from neutron induced reactions up to 20 MeV, and photonuclear reaction cross sections.

In this framework, relevant aspects of nuclear structure models and of evaporation and pre-equilibrium mechanisms are discussed together with a critical analysis of the related computing codes considered in present ENEA evaluations, aimed to produce specific contributions to the above mentioned nuclear programs and applications, and to co-operate in the framework of the international initiatives and efforts on the inter-comparison of the evaluated data and the relevant models and codes. Particularly, an innovative method has been developed and utilized for microscopic and statistical models of nuclear structure, especially referring to algebraic models and to superfluid models, in order to complement the adopted multi-step reaction model, as an unified framework for the treatment of pre-equilibrium and compound-nucleus processes. Moreover, microscopic algebraic model calculations are discussed , as they have been brought up to predict photonuclear reaction data in the present context.

Most significant results are presented from calculations relevant to some innovative structural materials in nuclear applications, namely Ti, V and Mo isotopes, in comparison with the presently available experimental values. Moreover, with regard to heavy nuclei reaction data, the effect of photo-fission channel is discussed for U and Th nuclides of main relevance, in a simple yet reliable model of statistical fission.

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## [203] Results of BRIC, the IntraNuclear Cascade code of Bruyères-le-Châtel

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Inelastic nuclear reactions induced by hadrons or light nuclei at intermediate energy may be modelized in two steps. The first step describes the interactions of energetic particles with nucleons of the target nucleus as individual collisions; particles are emitted in the continuum throughout this step that lasts 50-100 fm/c and the remaining nucleus is often highly excited. The IntraNuclear Cascade (INC) models are based on such approach. The second step treats the deexcitation of the residual nucleus by either sequential emission of nucleons and light nuclei or binary fission.

The INC models present some deficiencies especially in the production of nucleons at very forward and backward angles for incident energy not only below 200 MeV but also up to the GeV range. While a preequilibrium model is sometimes included between the two steps to correct most of these deficiencies, the INC code of Bruyères-le-Châtel named BRIC has been directly improved to give better results on wide ranges of the incident energy and of the mass of the target nucleus. For that some of the physics implicitly included in sophisticated nuclear dynamics models like BUU or QMD has been implementated in BRIC. While these sophisticated nuclear dynamics models have often a very high computing time,

BRIC is enough fast, even for reactions on heavy target nuclei, with reliable results to be a good event generator of the INC step in macroscopic transport codes like MCNPX for spallation studies.

We describe the physics of the BRIC model and present its results for various reactions of incident energy above 40 MeV/A.

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## [228] Advanced three-dimensional method for shutdown dose rate calculations

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The method was originated in designing activity for International Thermonuclear Experimental Reactor (ITER) and Demonstration Fusion Power Reactor DEMO projects. Fusion reactor has much heterogeneity, such as port of remote access, channels with diagnostic apparatus. In order to obtain precise value of shutdown dose rate it is necessary to take into account depositions to dose rate from surrounded radioactive reactor parts of residual gamma particles.

The principal feature of the method is performing calculations in three consistent stages: radiation 3-D transport during nuclear device operation, calculations of decay gamma sources, and decay gamma transport from sources in the chosen 3-D geometry with shutdown dose rate or afterheat as a result. Realization of the method is performed by means of interface code between radiation transport and activation programs. The neutron and decay radiation transports analyses were carried out by the Monte-Carlo MCNP program, the decay activation analysis - by the inventory program FISPACT. The interface automated the process of creation of input files for separate MCNP and FISPACT calculations on the basis of preliminary adjustment given by the user. The interface allows optimizing the process of activation analysis by revealing dominant sources of radioactive radiation. The developed interface essentially reduces time needed for calculations.

The general methodology of shutdown dose rate calculation has been invented for solving some particular tasks of radiation environment estimation in irradiated by neutrons nuclear devices, regardless of geometry complexity. Methodology works for any times after reactor shutdown, for any materials. The code is modernized and combined all advantages obtained in international work on development shutdown dose rate codes for fusion devices. One of the acceleration features of code algorithm is use multi-box Monte-Carlo sampling procedure in stage of decay gamma transport. Method realized in code was successful applied to ITER and DEMO fusion reactor projects.

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## [300] Light Cluster Production in the Cascade Stage of Spallation Reactions

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The Liege Intranuclear Cascade code INCL4 was recently shown to give, when coupled to the ABLA evaporation code[1], and without parameter tuning, very good results, for a large set of data concerning spallation reactions in the 100 MeV to 2 GeV range of incident energies [2]. In this reference, it is argued that the success of this model may come primarily from the self-consistent determination of the stopping time, i.e.the time at which the cascade is stopped and the evaporation code is started. This feature seems to free the model from the introduction of a so-called pre-equilibrium module. However, it is responsible for the lack of production of light clusters of nucleons with energy larger than those typical of evaporation (the so-called pre-equilibrium emission). Although the multiplicities of these kinds of clusters is rather low, their emission may have important implications for spallations sources. Indeed, many of these clusters correspond to gazeous elements, which are liable for modifications of the mechanical properties. It is thus crucial to have accurate predictions for the production of these elements.

Here, we report on a new model for light cluster production in the cascade stage and its implementation in the Liege INC model. The model may be described schematically as follows: (1) When a nucleon appears at the nuclear surface, it is checked whether it can drag a cluster along. (2) A cluster is defined as a group of nucleons sufficiently close to each other in phase space. (3) If the candidate nucleon belongs to a light and a heavier clusters at the same time, the preference for emission is given to the heaviest one. (4) To be emitted, the candidate cluster must, of course, have sufficient energy to overcome the threshold and succeed the usual probabilistic test for crossing the Coulomb barrier. (5) If no cluster can

be emitted, the candidate nucleon is emitted. There are two parameters in the model: one is used to determine the location at which the candidate nucleon is tested and the other one defines the closeness criterion on which clusters are built.

This model has been implemented in the numerical code INCL4 and predictions are compared with double differential cross-sections for light cluster (up to alpha's) production, measured by the NESSI group[3] on the p(2.5GeV)+Au systemand and at PSI on the n(540MeV)+Bi and n(540MeV)+Cu systems[4,5]. Good agreement is obtained with a single set of the parameters. The influence of the introduction of the cluster production in the cascade stage on particle multiplicities is also investigated. It is shown that globally more nucleons are ejected in this stage, but free nucleons are emitted less abundantly. Another consequence is the increase of the excitation energy at the end of the cascade stage, which helps to improve the predictions of Ref.[2] for the residue mass spectrum in the fragmentation region.

Finally, the phase space properties of the dynamically constructed clusters are exhibited.

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## [323] FISSION WITHIN THE SPALLATION PROCESS. INFLUENCE OF THE INTRA-NUCLEAR CASCADE AND EVAPORATION MODELIZATIONS ON THE FISSION FRAGMENT PRODUCTION

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The spallation process is usually described by two steps. The first one is an intra-nuclear cascade (INC) leading to an excited nucleus and fast particle emission and the second one is a deexcitation phase. The excited nucleus can deexcite by two ways: evaporation of particles (mainly nucleons, but also composites) and possibly fission in the case of heavy residues. Of course, the results depend a lot on the quality of the fission model, but the entrance parameters, i.e. the features of the fissioning nucleus, are obviously important as well. Consequently a precise description of the previous stages, INC and evaporation, is required. Indeed, the excitation energy, fissility parameter and angular momentum which are important for fission are given first by the INC and second by the following evaporation before fission. Using different INC models coupled to the same deexcitation model (ABLA from GSI) we have investigated the influence of these parameters. In particular, we show that taking into account d, t, $^3$He affects the previous calculated results (mass and charge distribution of the nuclei at the end of the spallation process). The angular momentum plays a significant role in the fission process for some nuclei. The momentum values are different according the cascade model one uses. We tried to understand the reasons and the impact on the fission products for two models that are INCL4 and ISABEL. The excitation energy distribution, which is predicted differently by the two models, is also an important parameter in the description of the fission process. For example, in INCL4 the stopping time of the INC and the emission of d, t, $^3$He and alpha are parameters which have a large influence on it. For this study we compare also our calculated results to recent experimental data.

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## [334] A new and consistent approach to deal with Pauli-blocking mechanism in nuclear reactions via intranuclear cascade processes

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The dynamical Pauli-blocking mechanism at multiple nucleon-nucleon scattering in nuclear reactions is investigated via the multicollisional Monte Carlo (MCMC) intranuclear cascade model. Differently from

other transport models so far used, which are based on a randomly generated nuclear ground state with a stochastic treatment of the Pauli-blocking, our model incorporates a shell-structured nuclear ground state where each nucleon is assigned to a single quantum state. The transition between the pre-equilibrium and evaporation phases is energetically determined, allowing the description of the cascade process without any free-parameter, such as some ambiguous stopping time parameters adopted in similar time-structured cascade models. The occupation number distribution after the cascade is calculated and propitiates a stringent test of confidence for our Pauli-blocking mechanism since the long-standing spurious depletion of the Fermi-sphere, usually present in other cascade models, no longer shows up. The quasideuteron channel is investigated, and we have found a blocking factor for the photoabsorption mechanism which is in overall agreement with previous results based on Fermi gas level-densities calculations. Experimental data of neutron multiplicities for Sn, Ce, Ta and Pb in the 20-140 MeV range are described fairly well by our model.

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## [340] The CRISP code for nuclear reactions

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The CRISP package performs the intranuclear cascade process and the evaporation/fission competition resulting in a code that represents a good tool to describe complexes characteristics of the nuclear reactions, and opens the opportunity for applications in different fields, such as medical physics, photonuclear reactions, spallation or fission process initiated by different probes and in Accelerator Driven Systems, where precise description of energetic and angular neutron distribution, neutron multiplicity and spallation products information are needed.

In the CRISP model, was included the time-sequence characteristics of the MCMC code and the evaporation/fission competition process model of the MCEF [1,2]. Also, includes improvements in the code, as the excitation of nucleonic resonances heavier than Delta; the initial nuclear ground state construction according to the Fermi model and Pauli principle; and a more realistic Pauli blocking mechanism. Some consequences of the improvements performed in the code will be discussed, as, e.g., the absence of Pauli Principle violations observed in the occupation number for single-particle bound states, and the absence the lack of the unphysical nuclear boiling, which shows up in some Monte Carlo code.

At the present two other reaction channels are being includes, namely, the quasi-deuteron mechanism at energies between 40 MeV and 140 MeV, and the photon hadronization process, which gives rise to the shadowing effect. With these modifications it will be possible to use the CRISP code for energies above 40 MeV up to a few GeV not only for reactions initiated by protons and neutrons, but also by photons.

We will describe some of the consequences resulting of these modifications and present some results in order to illustrate the possible applications, for which this package can be used, mainly those related to spallation process involving high energy protons.

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## [343] The Role of Transitional Levels to Explain the $^{237}$Np ($\gamma$,f) Cross Section Structures Near the Threshold

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The transition levels at the top of the two $^{237}$Np fission barriers were, for the first time, obtained by means of the so-called semi-microscopic combined method using Lipkin-Nogami projectors in the BCS approach which we have recently developed and implemented[1]. In order to overcome the difficulties in dealing with large nuclear deformations, we used the BARRIER code[2], which calculates single particle spectra in a deformed Woods-Saxon potential. The results enabled us to describe the experimentally observed near-barrier photofission cross section structures for $^{237}$Np[3]. In particular, the long standing issue on the physical nature of a $^{237}$Np($\gamma$,f) structure around $5.7 - 5.8$ MeV, systematically measured in the last three decades, was nicely elucidated in terms of a bunch of transition states at the top of the highest and inner barrier (height $\cong$ 5.7 MeV). Also, an experimentally observed sub-barrier shelf was identified as belonging to a bunch of levels at the top of the lowest and outer barrier (height $\cong$ 5.2 MeV).

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## [353] Level Densities in $^{56,57}$Fe

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Knowledge of the level density is important in many branches of nuclear physics, nuclear astrophysics and applied areas. Recently the Oslo group has extracted level densities for $^{56}$Fe and $^{57}$Fe nuclei from primary $\gamma$ spectra using ($^3$He, $\alpha\gamma$) and ($^3$He, $^3$He'$\gamma$) reactions on $^{57}$Fe target[1]. $^{56}$Fe nucleus has significant astrophysical importance. The modern view predicts the direct production of $^{56}$Fe isotope in terms of weak nuclear statistical equilibrium (NSE)[2].

In the present contribution we have calculated the level densities of $^{56}$Fe and $^{57}$Fe nuclei on the basis of realistic shell model and the BCS Hamiltonian with inclusion of pairing interaction [3]. The experimental nuclear level densities have been compared with the results obtained with the microscopic theory . These results together with the calculational procedure will be presented and discussed.

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## [358] Proton Radioactivity for Nuclei with $Z > 50$

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Ground and excited state nuclear properties for nuclei with Z>50 that exhibit proton radioactivity have been systematically compiled and evaluated. Level properties (energy, spin and parity, half-life, gamma-rays) as well as decay information (proton energy, Q-value and intensity) are presented. Q-values are compared with different nuclear mass theoretical models. Production cross-sections, normally in the micro-barn range or smaller, are also presented.

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## [418] Microscopic Investigation on the Electro-Magnetic Form Factors of Proton

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The present work is devoted to analyzing the electric and magnetic form factors of proton in the frame of relativistic constituent quark model, since the elastic nucleon form factors carry essential information of nucleon structure. Several existing facilities around the world have been currently going on special experimental studies. To facilitate our calculations, the light-front (LF) formalism of the relativistic three-body kinetics is adopted. We derived the formulae of both form factors in a way which can allow us to do computation easily. The proton LF wave function is chosen that can take into account the SU(6) breaking effects and has a radial Gaussian ansatz with harmonic oscillator parameters. The calculations of six-dimension integrals are performed by using Monte Carlo method. Related computational results are presented and discussed. It is found the numerical results of the ratio of proton electric and magnetic form factors are in the satisfying consistence with the recent measured results.

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## [422] Assessment of Approximate Methods for Width Fluctuation Correction

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Hauser-Feshbach formula for Compound Nucleus cross section is known to be invalid when only a few reaction channels are competing. This so called width fluctuation effect is commonly treated in terms of two approximate methods: the one by Moldauer and the other one known as HRTW. Later, an exact solution to the problem has been formulated by the Heidelberg group in a form of the triple-integral formula. This approach, however, involves lengthy computation and approximate approaches continue to be used in reaction calculations.

Using the exact triple-integral expression for compound nucleus cross section as a benchmark, the accuracy of the HRTW and Moldauer approximation methods is compared for a wide range (more than 8000) of physically plausible cases. The Moldauer method is found to give superior results, although still with significant errors for weak elastic cross section. An improved formula for the elastic enhancement factor is presented and assessed, and is shown to improve accuracy of both methods. Finally, the convergence to exactness of the approximate methods in the high-absorption limit is investigated.

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## [423] RIPL-2: Reference Input Parameter Library for Nuclear Reaction Model Calculation

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RIPL-2 is a comprehensive library of input parameters for theoretical modeling of nuclear reactions developed under the IAEA Coordinated Research Project and released in May 2003. It contains extensive compilation of physical quantities that are necessary for calculation of nuclear reactions including nuclear masses, deformations, level schemes, optical model potentials, level densities, gamma strength functions, and fission barriers. Contents of the RIPL-2 library, data testing and their retrieval from the IAEA Web site will be reviewed. Limitations of the current library and future improvements (RIPL-3) will be discussed.

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## [426] Validation of the Monte Carlo Pre-equilibrium Module HMS

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The HMS preequilibrium module has been benchmarked in the extensive calculations of (N, N) spectra compared against experimental data. Angle integrated spectra of neutron and protons were calculated with EMPIRE-2.19 code for selected targets using (i) pure Hauser-Feshbach (HF) model and (ii) combined HF and HMS approach. Comparison with the compound nucleus results (HF) was essential for observing actual effect of the preequilibrium emission and screening the results for deficiencies due to the parameterization of the statistical part rather than to the HMS model itself.

The preequilibrium yields in the HMS model are governed by the damping rate, which can be adjusted (by k-factor) to fit experimental data. In the present analysis we have found no need for such an adjustment on a global scale. The mass and incident energy dependence of the HMS predicted nucleon emission was found to be correct. The encountered discrepancies, in most cases, can be ascribed to the oversimplified global parameterization of the Hauser-Feshbach component. The only potential deficiency in the HMS model is the over-prediction of the emission in the charge exchange channels.

We conclude that damping width as calculated in the HMS model is correct and does not need any modification on a global scale. In particular cases minor adjustment of the k-factor may improve performance of the model.

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## [431] Merging the CEM2k and LAQGSM Codes with GEMINI

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During recent years, we have developed at LANL an improved version of the Cascade-Exciton Model (CEM) of nuclear reactions realized in the code CEM2k and the Los Alamos version of the Quark-Gluon String Model (LAQGSM) to describe reactions induced both by particles and nuclei at energies up to hundreds of GeV/nucleon for a number of applications. Originally, both CEM2k and LAQGSM were not able to describe fission reactions and production of light fragments heavier than $^4$He, as they had neither a high-energy-fission nor a fragmentation model. Recently, we addressed this problem by further improving our codes and by merging them with several evaporation/fission/fragmentation models. Here, we present results of merging CEM2k and LAQGSM with the well-known sequential-binary-decay model GEMINI by Charity. We present some results on proton- and nucleus-induced fragmentation and fission reactions predicted by these extended versions of CEM2k and LAQGSM.

We show that merging CEM2k and LAQGSM with GEMINI allows us to describe many fission and fragmentation reactions in addition to the spallation and evaporation reactions which are already relatively well described. Nevertheless, the current version of GEMINI merged with CEM2k and LAQGSM does not provide a completely satisfactory description of some complex particle spectra, fragment emission, and spallation yields for some reactions, and is not yet a universal tool for applications. Our results show that GEMINI is a powerful approach to describe evaporation/fission/fragmentation reactions and often provides better results in comparison with other modern models, especially for emission of heavy fragments from reactions on medium-heavy nuclei (where most other models simply fail), but it must be further extended and improved in order to properly describe arbitrary reactions.

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## [437] Improvement of the fission channel in the EMPIRE II code

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Modeling of the fission channel in the EMPIRE-2.18 code was only adequate for heavy ion induced reactions. Version 2.19 (Lodi) of the code introduces an advanced fission formalism applicable also to the multi-chance fission induced by low energy nucleons.

Light particle induced fission proceeds through the formation of the compound nucleus treated in EMPIRE-II within Hauser-Feshbach and HRTW models. The expression for the fission probability, as used in the 2.19 version, is derived in the frame of the optical model for fission. It describes the transmission through a multi-humped barrier starting from the sub-barrier excitation energies. Using this generalized relation, it is possible to reproduce experimental fission cross sections (including the resonant structure observed in fertile nuclei) and to set up a general procedure for determining parameters describing fission barriers associated with the transition states.

In the first run EMPIRE automatically creates auxiliary input file with parameters describing discrete fission barriers and level densities at the saddle points. These values are taken from RIPL-2, from internal systematics, or are calculated by the code. For the level densities at the saddle points the HF-BCS results of RIPL-2 or the dynamical approach specific to EMPIRE (accounting for collective enhancements and nuclear shape asymmetry at each saddle) can be used. The user can easily modify fission related parameters by editing the existing input file.

Encouraging results indicate that improvement of the fission channel extends applicability of the EMPIRE code to the interaction of low energy neutrons with the actinides, which is of primary importance for various applications.

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## [442] Nuclear Mass Predictions Within The Skyrme HFB Theory

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To increase the reliability of predictions of nuclear masses at the neutron-drip line we systematically analyze the sensitivity of Hartree-Fock-Bogoliubov (HFB) mass formulae to various physical inputs, such as a density dependence of the pairing interaction, a low effective mass, the symmetry energy, the particle-number projection, ... We typically use a 10-parameter Skyrme force and a 4-parameter $\delta-$function pairing force. The 14 degrees of freedom are adjusted to the masses of all measured nuclei with $N, Z \geq 8$ given in the 2001 and 2003 Audi-Wapstra compilations. The masses of light and proton-rich nuclei are corrected by a 4-parameter phenomenological Wigner term. With more than ten such parameter sets complete mass tables are constructed, going from one drip line to the other, up to Z=120. These HFB masse tables are compared with previously published HFBCS and FRDM masses.

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## [449] Photonuclear reactions in FLUKA: cross sections and interaction models

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Photonuclear reactions were implemented in the FLUKA general-purpose multi-particle transport code about ten years ago, opening the way to a more accurate design, fully based on Monte Carlo, of electron accelerator shielding. Since then, photonuclear reactions have been introduced also in other codes: but the strategy chosen for the FLUKA implementation, aimed at covering all nuclei over the whole energy range, probably remains still unique.

The FLUKA scheme is based on four physical models corresponding to different energy ranges but partially overlapping to ensure continuity. All models are smoothly integrated in the FLUKA hadronic event generator (Generalized Intranuclear Cascade, Preequilibrium and Evaporation).

In the lowest energy range, Giant Resonance total cross sections have been derived from experimental data or from existing evaluations for 190 nuclides; for all other nuclei, excitation functions are obtained

from parametrizations or by interpolation. Many partial cross sections, not used explicitely in FLUKA, have also been evaluated in order to ensure consistency of the total cross sections entered into the database.

The FLUKA capability to simulate nuclear reactions due to both real and virtual photons has been successfully used in recent years to calculate not only electron accelerator shielding, but also activation of soil and accelerator structures, detector background and muon production by high-energy cosmic gamma rays.

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## [456] Analysis of Spallation and Fission Fragment Residues for Lead Isotopes Irradiated by Protons at Energies below 1.0 GeV

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Spallation and fission residues produced by the proton irradiation of $^{206}$Pb, $^{207}$Pb, and $^{208}$Pb targets at energies from 40 MeV up to 1 GeV have been studied recently at ITEP. These data allow testing various versions of the intranuclear cascade models widely used for simulation of spallation product yields. Main differences between codes are briefly reviewed. Modifications of the LAHET, CASCADO, and CAMO codes, that are required to reduce deviations from experimental data, are discussed.

Special attention is attracted to an improvement of the preequilibrium emission description in different codes. Recent experimental data on spectra and integral yields of light charged particles for energies below 150 MeV are used to test the selected parameters of preequilibrium emission simulation for the cascade models considered.

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## [476] The McGNASH Nuclear Reaction Code: Progress Status

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The McGNASH nuclear reaction code is being written at Los Alamos as a modern version of the well-known GNASH code which has been used successfully over the years in numerous reactions cross sections calculations and nuclear data evaluations. As its predecessor, McGNASH implements the Hauser-Feshbach statistical decay theory of the compound nucleus. It uses (uncollapsed) transmission coefficients T(l,j) obtained from optical model calculations, and accounts for non-statistical corrections such as width fluctuation corrections at low incident energies (HRTW, Moldauer, GOE), and preequilibrium particles emission within the HMS hybrid model. The fission channel representation follows the GNASH implementation of the double humped fission barrier. Level densities are calculated with the Ignatyuk form of the Fermi-gas model, and the Kopecky-Uhl generalized Lorentzian formalism is used to calculate $\gamma$-ray strength functions.

McGNASH is written in modern Fortran 95, and is designed to be highly modular, allowing for a rapid and constant development. The user input interface has been simplified considerably as compared to older GNASH input files. Note that McGNASH, during this development phase, is constantly being tested against GNASH results and experimental data.

We will report on the current status of the code development, and on some recent calculations aimed at testing and demonstrating the new capabilities of McGNASH.

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## [5] Neutron Activation Data for Neutron Interrogation Applications

Donald L. Smith

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Various schemes have been proposed for active neutron interrogation of containers or luggage, with the intent of locating concealed contraband items such as conventional explosives or restricted special nuclear materials. Relatively intense and energetic neutron sources are usually required in these applications in order to penetrate the containers and to provide unambiguous characteristic signals that are well above background, thereby minimizing both false positives and negatives. Consequently, neutron irradiation of the contents of certain containers during the interrogation process could lead to the production of significant residual activity. This, in turn, might either limit or prevent the application of these methods in those situations where there is a potential for unacceptable public exposure to the induced secondary radiations. This study seeks to identify those particular neutron activation reactions that might be problematic in this context, and it reviews the current status of the pertinent evaluated cross section data available from the major general purpose and special purpose data files for neutron energies up to 20 MeV.

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## [36] Measurements at n_TOF of the Neutron Capture Cross Section of Minor Actinides relevant to the Nuclear Waste Transmutation

Daniel Cano-Ott

*CIEMAT (Madrid - Spain) on behalf of the n_TOF collaboration*

Accurate and reliable neutron capture cross section data for actinides are necessary for the proper design, safety regulation and precise performance assessment of transmutation devices such as Fast Critical Reactors or Accelerator Driven Systems. In particular, the neutron capture cross sections of $^{237}$Np, $^{240,242}$Pu, $^{241,243}$Am and $^{245}$Cm play a key role in the design and optimization of a strategy for the Nuclear Waste Transmutation. For this reason, the afore mentioned cross sections will be measured in 2004 at n_TOF with high accuracy due to a combination of features unique in the world: high instantaneous neutron fluence and excellent energy resolution of the n_TOF facility, innovative Data Acquisition System based on flash ADCs and the use of a high performance $BaF_2$ Total Absorption Calorimeter as a detection device. The experimental technique will be described and preliminary experimental data will be presented at the time of the conference.

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## [38] An Analysis of the Nuclear Data Libraries Impact on the Criticality Computations Performed using Monte Carlo Codes

ELENA DANIELA N. GUGIU

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The major aim of the work is a sensitivity analysis related to the impact of the different nuclear data libraries on the criticality calculations performed for various CANDU fuel projects, and on the simulations related to the replacement of the original stainless steel adjuster rods by cobalt rods in CANDU 6 reactor core.

The criticality calculations and the void effect estimations for various CANDU fuel types are performed using the Monte Carlo transport codes MCNP5 and MONTEBURNS 2.0. The simulations are performed for the actual, detailed geometry and material composition of the fuel bundles and reactivity devices. The computations are performed for fresh fuel, and for various burnup point values, as well. Some comparisons with deterministic and probabilistic code results (involving WIMS library) are also presented.

The analysis of the results show that: 1) different neutron cross-section releases for the same isotope could induce changes in the k-infinity value; 2) MCNP/ WIMS calculations performed for various burnup values point out the impact of the pseudo-fission products library (WIMS) on k-infinity values; 3) the accuracy of the MONTEBURNS criticality computations is influenced by the values of the isotope importance fractions, and especially by the cross-section libraries for the fission and pseudo-fission products.

The computations related to the replacement of the stainless steel adjuster rods by cobalt rods are also performed using MCNP5 and MONTEBURNS codes.

The impact of the cross-section temperature dependency and of the neutron capture cross-section to metastable states on the neutronics simulations, as well as on the Cobalt dose and heating evaluations is also investigated in the present work. Uncertainty effects and their limitations are also analyzed.

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## [60] Compton profile cross-sections: Utilization of the data for medical and biological applications

Donepudi V. Rao, Takao Akatsuka

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Compton profile cross-sections are evaluated at a number of energies in order to utilize them for medical and biological applications. Compton profile is a correction to the Klein-Nishina cross-section taking into account the motion of the electrons. This correction modifies the shape of the Compton peak and depends on the chemical elements in the compound analyzed. Thus, the Compton Profile can be used as a probe for the electronic structure of atoms or molecules. Based on this formalism, Compton profile cross-sections and Compton energy absorption cross-sections, for few biological materials are evaluated, for example, water, bone and adipose tissue. However, the shape of the Compton peak is also influenced from the geometrical factors or apertures of collimators used in the experimental setup. This paper also concerns a study about the influence of the geometrical broadening on the discrimination of different biological elements.

Utilization of the data for medical and biological applications:

In dosimetry calculations, use is frequently made of the Compton energy absorption cross-section per electron ($\sigma_{en}$), which expresses the probability of transfer of energy from a photon to an electron by the Compton process. It is equal to the total Compton scattering cross-section per electron ($\sigma_{TC}$), times the fraction ($f$) of photon energy which is converted to kinetic energy of the recoil electrons in a single collision, averaged over all directions of electron recoil ($\sigma_{en} = \sigma_{TC} f$). Since the range of the recoil electron is small, the Compton energy absorption cross-section per electron is a measure of the total energy communicated locally to the absorbing medium by the Compton process. The most intense Compton scattering is produced in the atomic region $1 \leq Z \leq 20$. For example, most biological and phantom materials of medical interest containing varying proportions of the elements in the above atomic region. It is an attempt to know the effect of Doppler broadening for single atoms, many of which constitute the biological materials. One particular area of interest for these values is in Monte Carlo simulation of photon transport in applications of medical physics.

The impact of Compton profile data on the computations of X-ray cross-section and attenuation coefficients seems not has been explored fully in the literature. The main task of the present work is to examine the Compton profile literature and explore what, if any, effect our knowledge of this line broadening has on theoretical computations of photon incoherent scattering cross-sections and total mass attenuation coefficients. Further, to generate the tables of total Compton, individual shell and Compton energy absorption cross-sections by means of double differential scattering cross-sections based on impulse approximation with the inclusion of Doppler broadening. This type of new tables is not available in the literature and will be useful for comparison, compilation and simulation purposes for medical and biological applications.

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## [78] Inverse kinematics studies of intermediate energy reactions relevant for single event effects in microelectronics and medical applications

J. Aichelin[1], J. Blomgren[2], A. Budzanowski[3], M. Chubarov[4], C. Ekstroem[5], B. Jakobsson[6], A. Kolozhvari[5], O. Lozhkin[4], Yu. Murin[4], P. Nomokonov[7], N. Olsson[2], H. Persson[5], V. Pljuschev[4], I. Skwirczynska[3], H.H.K. Tang[8], P.-E. Tegner[9], Y. Watanabe[10], L. Westerberg[5], M. Zubkov[4]

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A new experiment is under preperation to run in April 2004 at The Svedberg Laboratory (TSL) in Uppsala, Sweden. The basic objective is to measure both light and heavy secondary fragments produced from intermediate energy nucleon-nucleus reactions, by applying inverse kinematics techniques and exploiting the unique features of the CELSIUS storage ring at TSL. This project has been largely motivated by two important areas of applications: single event effects (SEEs) in microelectronics and proton beam cancer therapy. High-quality data of secondary fragments and recoils provide stringent constraints for nuclear reaction models that generate critical inputs for realistic SEE simulation models and accurate dosage distribution calculations. The scarcity of such essential recoil data has rendered our research proposal timely. Here we report the first results that demonstrate the feasibility of our experimental setups.

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## [90] Monte-Carlo Calculations of Core Reactivity and Fluxes for the Development of a BNCT Neutron Source at the Kyiv Research Reactor

Olena O. Gritzay[1], Olexandr I. Kalchenko[1], Nataliya A. Klimova[1], Volodymyr F. Razbudey[1], Andriy I. Sanzhur[1], Stephen E. Binney[2]

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The WWR-M Kyiv Research Reactor (KRR) is a light water moderated and cooled tank-type reactor with a beryllium reflector. The reactor currently uses 36 % enriched uranium-235 WWR-M2 fuel assemblies, each of which consists of an outer hexagonal tube and two inner cylindrical tubes. The nominal thermal power is 10 MW. Today the KRR is used for various purposes, including neutron physics, materials research, radioisotope production, neutron transmutation doping of silicon, and other applications. One of the ten horizontal tubes is a thermal column with a graphite moderator. In accordance with preliminary calculations [1-3] this tenth horizontal channel will be transformed into an epithermal neutron source with parameters that meet the requirements of BNCT by replacing the graphite blocks with new moderators, filters, collimators, and shielding. The addition of a uranium converter will further improve the parameters of the neutron beam.

The purpose of our Monte-Carlo calculations was to show that replacement of the graphite blocks in the thermal column with new moderators, reflectors, and filters and also installation of a uranium converter close to the reactor core does not reduce the safety of the KRR. The Monte-Carlo calculation model of the reactor takes into account almost all of the KRR details, including the reactor tank, the hexagonal core geometry (about 220 WWR-M2 fuel assemblies, eight control- and safety-rods, a regulating rod, and peripheral beryllium assemblies), vertical irradiation channels, the thermal/epithermal column, reflectors, etc.

The comparative analysis of core reactivity and fluxes, calculated with the existing thermal column and with the reconstructed epithermal one, has shown that at the KRR an epithermal neutron flux may be achieved matching the parameters required for BNCT while preserving the same level of reactor safety.

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## [98] High resolution cross section measurements on $^{206}$Pb and the impact on the status of the cross section data for Pb-Bi target, coolant and moderator systems

Borella[1], Brusegan[1], Schillebeeckx[1], Aerts[2], Berthoumieux[2], Gunsing[2]

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The most promising Accelerator Driven System (ADS) will be based on the use of Lead-Bismuth eutectic as spallation target, coolant and moderator. Therefore, for the design, optimisation and safety assessment of such systems, the nuclear data for neutron induced reactions in $^{204,206,207,208}$Pb and $^{209}$Bi play an important role. For high energies, above the resonance region, A.J. Koning and collaborators

produced a revised evaluated data file for Pb and Bi isotopes. Their evaluation, using the TALYS code, includes the recent cross measurements of the HINDAS project. In the resolved resonance region, the available experimental data for Pb-isotopes and $^{209}$Bi result from measurements primarily focused on fundamental physics research, such as doorway states in closed shell regions, and to astrophysics applications. The total and partial cross section measurements were not performed in support to a specific programme related to the nuclear fuel cycle. These considerations express the need for improved nuclear data for ADS and fast reactor technologies in the resonance region for Pb isotopes and of $^{209}$Bi. At GELINA we started $^{206}$Pb transmission and capture cross section measurements in an energy range from the eV region up to 500 keV, with a time resolution (1 ns) that was not reached before. The capture measurements together with a resonance shape analysis are finalised. A comparison of our resonance data for $^{206}$Pb with the data used for the present evaluations reveals discrepancies up $20-30\%$. These discrepancies result from systematic uncertainties due to angular correlation effects, the neutron sensitivity of the detectors and the use of weighting function not accounting for the gamma transport in the sample. Since the evaluated data for $^{204,207,208}$Pb and $^{209}$Bi are based on similar experiments, these data will suffer from similar systematic uncertainties.

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## [101] Some applications of Neutron-Resonance-Capture-Analysis

Borella[1], Schillebeeckx[1], Siegler[1], Perego[2], Postma[2], Van Aken[3]

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Neutron Resonance Capture Analysis (NRCA) has been developed in a joint effort by IRI and IRMM as a new method for analysing the elemental composition of materials and objects. It is based on the occurrence of resonances in neutron capture at energies typical for each element (isotope). Energies of captured neutrons can be determined with the Time-Of-Flight (TOF) method using a pulsed neutron source and detecting the prompt gamma-radiation following neutron capture. Since it is not necessary to determine the energies of the prompt gamma-rays and since most of the capture events are followed by cascades with about 3 to 6 prompt gamma-rays, it is possible to achieve large detection efficiencies using a set of scintillation detectors [1]. It is a fully non-destructive method, that is applicable to many elements, determines the bulk elemental composition, does not require any sample preparation, and results in a negligible residual activity. We have applied NRCA in studies of a series of bronze (pre)-historic artefacts from various sources. We consider exploitation of NRCA for other purposes, notably to detect neutron-absorbing isotopes for nuclear materials in order to quantify impurities in reference materials, to verify the presence of lanthanides in reprocessed fuel and to detect the presence neutron poison in bulk uranium samples. Recently we started the latter application in collaboration with FBFC using pellets of uranium oxide mixed with some gadolinium oxide.

[1] H.Postma et al., J. Radioanalytical and Nuclear Chemistry, 248 (2001) 115

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## [104] Study on the Possibility of using LLFP as Burnable Poison for Transmutation

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Transmutation of long-lived fission products is one of the key issues in development and utilization of nuclear power in the world. In the study underway we are trying to replace the burnable poison in LWR by a mixture of some LLFPs. Main fission product isotopes included in high level waste (HLW) with half life less than 15 years are: $^{85}$Kr, $^{93m}$Nb, $^{102}$Rh, $^{106}$Ru, $^{109}$Cd, $^{113m}$Cd, $^{125}$Sb, $^{134}$Cs, $^{146,147}$Pm, $^{152,154,155}$Eu, $^{171}$Tm within 15 and 30 years are: $^{90}$Sr, $^{137}$Cs, $^{121m}$Sn within 30 and 90 years is: $^{151}$Sm, within 100 and 20000 years are: $^{94}$Nb, $^{108m}$Ag, $^{158}$Tb, $^{166m}$Ho and more than 20000 years are: $^{79}$Se, $^{93}$Zr, $^{94}$Nb, $^{99}$Tc, $^{107}$Pd, $^{126}$Sn, $^{129}$I, $^{135}$Cs. Our main objectives are: (1) to calculate the atomic density of each LLFP in the mixture with reactivity equivalent to the reactivity of boron used in LWR, (2) to calculate the absorbed neutrons in LLFPs as compared to burnable poison, (3) to calculate the transmutation rate and the change of reactivity. The advantage of using LLFPs is the closeness of neutron spectrum

in burnable (LLFP) rods and fuel rods. In the calculation we use ENDF/B6 and JENDL-3.2 libraries. Preliminary calculation is promising and needs more elaborate calculations.

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## [138] Measurements of deuteron-induced activation cross sections for IFMIF accelerator structural materials

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The IFMIF (International Fusion Materials Irradiation Facility) is an accelerator-based D-Li neutron source designed to test fusion reactor candidate materials for high fluence neutron. In the design of the IFMIF there are two 40 MeV deuteron linear accelerators with each 125mA beam current and long-term operation with total facility availability of at least 70% is conceived. However, activation of the structural materials along the beam transport lines by deuteron beam loss limits maintenance and makes long-term operation difficult. Thus the accurate estimation of deuteron-induced activity and the selection of structural materials are important in order to determine the beam loss criteria.

In this work, measurements of deuteron-induced activation cross sections for aluminum, copper and tungsten were performed by using a stacked-foil technique. Aluminum is the main component of the beam tube and chamber. Copper is used in the cavity walls, electrodes and magnetic conductors. For beam slits and coating to protect the beam facing materials, high-Z materials (tantalum, gold, tungsten, etc) are candidate materials. The stacked-foil consisting of aluminum, copper and tungsten foils were irradiated with deuteron beam at the AVF cyclotron in TIARA/JAERI. After irrdiation, the decayed gamma-rays emitted from the foils were observed by Ge detector. The $^{65}$Zn activities observed from copper foils and the $^{nat}$Cu(d,x)$^{65}$Zn reaction cross sections were used for monitoring the intensity of deuteron beam. The averaged deuteron energy in each foil position was calculated with the IRACM code. We have obtained the activation cross sections for the reactions $^{27}$Al(d,x)$^{27}$Mg, $^{24}$Na, $^{nat}$Cu(d,x)$^{62,63}$Zn, $^{61,64}$Cu, and $^{nat}$W(d,x)$^{187}$W, $^{181-184,186}$Re in 22-34 MeV region. The present results will be compared with other experimental ones and the data in the ACSELAM library and the measurements in above 34MeV and below 22MeV region will be performed in the near future.

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## [142] New Results on $CaH_2$ Thermal Neutron Scattering Cross Sections

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Calcium hydride ($CaH_x$) is a compound of interest in the frame of a current research programme on the transmutation of long-lived nuclear wastes. Indeed, since $CaH_x$ is relatively stable in liquid sodium, it is one possible material that can be used for local moderation of the neutron spectrum in fast reactors such as PHENIX. In order to describe the moderated region from Monte Carlo and/or deterministic calculations, thermal neutron scattering data are needed. In particular, an adequate treatment of the thermal inelastic scattering cross sections for bound hydrogen is requested. The present work aims at the determination of these data.

The first step consisted in the measurement of the phonon frequency spectrum, which was carried out on the three axis spectrometer of the Institut Laue Langevin in Grenoble (France). This phonon frequency spectrum has already been published and so only a brief description of this measurement is given. Then, from physical grounds, the acoustic mode has been weighted relative to the optical modes in order to treat Hydrogen atoms bound in $CaH_x$. The S($\alpha$,$\beta$) scattering laws have been generated for various temperature using the NJOY code working in the incoherent approximation and the Gaussian approximation. The $\alpha$ and $\beta$ grids used allow energy transfers of almost 2 eV at T=296 K. The deduced incoherent elastic and incoherent inelastic cross sections are presented, and the impact of the weighting factor, the grid definition and the order phonon expansion on these cross sections are discussed. In addition, the average displacement of proton in $CaH_2$ was calculated from our Debye-Waller integral and compared with previous values.

These new thermal neutron scattering data will be included in the JEFF3 European library.

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## [152] A Set of Critical Loading Configurations of the IPEN/MB-01 Reactor

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During 15 years, IPEN/MB-01 reactor has been operated jointly by IPEN and CTMSP to perform several experiments in order to validate calculational methods and related nuclear data libraries. Recently, IPEN has been invited to participate on the ICSBEP ( International Criticality Safety Evaluation Project). As a first task, IPEN has been engaged in a series of experiments in the IPEN/MB-01 core in order to evaluate critical configurations for a great number of practical applications. The main purpose of this work to contribute to ICSBEP proposing such set of configurations as benchmarks. The selected configurations in a total of five comprises the IPEN/MB-01 core surrounded by a stainless steel baffle and for some configurations consider the presence of burnable posion rods ($Al_2O_3$-$B_4C$; 5% mass content of B-10). The criticality condition was determined by means of a reactimeter plus an artifact based on the isothermal reactivity coefficient. Since the IPEN/MB-01 core possesses an average reactivity coefficient of around $-6.0$ pcm/C in the rage of 16 through 20 C, the procedure adopted was to decrease the reactor temperature up to 16 C, to criticalize the reactor in this condition, to increase the power to 1.0 W in order ot have a good statistics and finally to steadly increase the temperature up to 20.5C and stabilize the system. The final reactivity is obtained by the reactimeter removing all the control rods from the core. from this approach it could be obtained very high accuracy on the measured reactivity. The criteria was to choose configurations that has reactivity excess either positive or negative less than 10pcm. The final data takes care of the uncertainty due to manufactures ( Input data) and was considered to be less than 50 pcm. The calculational approach of the fivew critical configurations consider MCNP-4C ( ENDF/B-VI.8 library) an SCALE 4.4a systems. The results are consistants for a criticality analyses point of view.

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## [156] Nuclide Compositions and Total Activity of Spent MTR-HEU Fuel Elements of the IAN-R1 Research Reactor.

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With cooperation of the International Atomic Energy Agency (IAEA) and the Department of Energy (DOE) of the United States, several calculations and tasks related to the waste disposal of spent MTR fuel enriched nominally to 93% were carried out for the conversion of the IAN-R1 Research Reactor from MTR-HEU fuel to TRIGA-LEU fuel. In order to remove the spent MTR-HEU fuel of the core and store it safetly, a program was established at the Instituto de Ciencias Nucleares y Energìas Alternativas (INEA). This program included training, acquisition of hardware and software, calculations, design and construction of a decay pool, transfer of the spent HEU fuel elements into the decay pool and his final transport to Savannah River Site in United States.

In this paper are presented data of activities calculated in Ci for each relevant radionuclide present in the spent MTR-HEU fuel elements of the IAN-R1 Research Reactor, and data of photon production rates are also presented. The calculation takes in consideration data of fission products, activation products and actinides. The results obtained in this paper were used for shielding calculations in the design of the decay pool besides the dosimetric evaluations for transfering operations of the MTR-HEU fuel elements of the IAN-R1 reactor into the decay pool.

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## [167] 3-D NEUTRONICS-LINKED HYDRODYNAMICS CALCULATIONS FOR INERTIAL FUSION TARGETS

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Pulsed-power driven inertial confinement fusion (ICF) has shown promising results over the past few years, with the development of intense soft X-ray sources based on wire-array implosion. Neutronics

and radiative transport play an important role in determining the evolution of reactor-scale ICF targets. Numerical simulation through partially-coupled one-dimensional hydrodynamic and neutron transport codes has been reported for X-1 targets and light ion fusion LIBRA-SP targets [1-3] for computing neutron transport and hydrodynamic evolution of various types of targets. These studies have two major limitations. Firstly, they are limited to 1-D geometries. Secondly, they do not utilize the energy deposition due to neutron slowing-down in the hydrodynamic calculations, which can be important in reactor-scale pellets.

In the present study, we use a three-dimensional Monte Carlo neutron transport code along with a modified form of the 2-D axisymmetric radiation-hydrodynamics code MULTI-2D [4]. The modified form of Multi-2D uses the Lagrangian approach and allows fairly complex, multi-material geometries. Our calculation starts around the point of peak compression of the ICF target, with pellet parameters taken from Refs.[1-3]. At selected time-points (snap-shots) in the radiation-hydrodynamic simulation, the neutron flux distribution is determined, using the spatial distribution of fusion reaction rate as the source term for neutron transport. The energy deposition arising due to neutron slowing-down is also taken into account.

Apart from snapshots of the neutron flux distribution, the simulation yields the temporal, 2-D evolution of parameters such as the matter and radiation temperatures, density, pressure and the velocity field. It also yields the neutron spectrum emerging at the surface of the pellet, which is useful for comparison with diagnostics.

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## [169] NEW CROSS SECTION DATA FOR PRODUCTION OF THE THERAPEUTIC RADIONUCLIDES $^{64}$Cu, $^{140}$Nd and $^{192}$Ir.

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The use of radionuclides in internal radiotherapy is gaining significance. In this regard, radionuclides emitting $\alpha$-particles, low-energy $\beta$-radiation, or conversion and Auger electrons are needed. We investigated the formation of $^{64}$Cu, $^{140}$Nd and $^{192}$Ir via novel routes. The radionuclide $^{64}$Cu ($T_{1/2}$ =12.7 h, $E_{\beta^-}$ = 0.6 MeV, $E_{\beta^+}$ = 0.7 MeV) is interesting because of its suitable half-life and low energy $\beta$-radiation. It has the extra advantage of in-vivo detection via Positron Emission Tomography (PET). The radionuclide $^{140}$Nd ($T_{1/2}$ =3.37 d, 100 % EC, no $\gamma$-radiation) is almost a pure Auger-electron emitter. The available database for its production is rather weak. The radionuclide $^{192}$Ir ($T_{1/2}$ = 78.83 d, $E_{\beta^-}$ = 0.7 MeV) is well established in therapy. However, since it is commonly produced in a reactor, it is of low specific activity. We report on cross sections of the reactions $^{66}$Zn(d,$\alpha$)$^{64}$Cu, $^{nat}$Ce($^3$He,xn)$^{140}$Nd, $^{141}$Pr(p,2n)$^{140}$Nd, and $^{192}$Os(p,n)$^{192}$Ir measured using the stacked-foil technique:

- The $^{66}$Zn(d,$\alpha$)$^{64}$Cu reaction was studied radiochemically over the energy range of 5 to 14 MeV. The excitation function showed a maximum of about 25 mb at 11 MeV. These are the first measurements on this reaction using highly enriched $^{66}$Zn (99.0 %). A comparison of this reaction with the most commonly used production route, namely the (p,n) reaction on highly enriched $^{64}$Ni, will be given.

- The $^{nat}$Ce($^3$He,xn)$^{140}$Nd reaction was studied from 15 to 36 MeV. The disturbing side reactions $^{nat}$Ce($^3$He,xn)$^{139m,g,141m,g}$Nd were also investigated. A maximum cross section of about 900 mb at 27 MeV was obtained for the $^{nat}$Ce($^3$He,xn)$^{140}$Nd reaction. The results deduced via direct X-ray counting and measurement of the annihilation radiation of the daughter nuclide $^{140}$Pr were compared.

- Measurements on the $^{141}$Pr(p,xn)$^{140,141m,g}$Nd reactions were done from 10 to 45 MeV. The $^{141}$Pr(p,2n)$^{140}$Nd reaction shows a maximum cross section of about 850 mb at 18 MeV. A comparison of the two production

routes of $^{140}$Nd, viz. $^{nat}$Ce($^{3}$He,xn)$^{140}$Nd and $^{141}$Pr(p,2n)$^{140}$Nd reactions, will be presented.

- Measurements on the $^{192}$Os(p,n)$^{192}$Ir reaction are underway using natural and isotopically enriched osmium targets over the proton energy range of 5 to 20 MeV. The shape of the excitation function appears to be similar to that of other (p,n) reactions in this mass region.

Differential and integral yield calculations of the desired radionuclides via the investigated reactions are being performed and the suitability of these reactions for production of the respective therapeutic radionuclide will be discussed.

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## [171] Validation and upgrading of the recommended cross section data of charged particle reactions used for production of gamma emitter diagnostic radioisotopes

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A recommended charged particle cross section database was published by IAEA, Vienna in 2001 (IAEA-TECDOC-1211. (2001), http:/www-nds.iaea.org/medical) under the title "Charged particle cross-section database for medical radioisotope production: diagnostic radioisotopes and monitor reactions". The database is divided into three main parts: monitor reaction, production of gamma emitter diagnostic radioisotopes and production of PET radioisotopes.

An upgrade and validation test of the database was performed and published for the PET isotope production reactions in 2003 to improve the quality and increase the reliability of the corresponding part of the database. As a continuation of that work the cross sections of nuclear reactions in which gamma emitter radioisotopes are produced were investigated. The experimental cross section data published earlier or measured recently and not yet included in the evaluation work of IAEA were collected and added to the primary database in order to improve the quality of the recommended data. The following reactions are considered: $^{67}$Zn(p,n)$^{67}$Ga, $^{68}$Zn(p,2n)$^{67}$Ga, $^{111}$Cd(p,n)$^{111}$In, $^{112}$Cd(p,2n)$^{111}$In, $^{123}$Te(p,n)$^{123}$I, $^{124}$Te(p,2n)$^{123}$I, $^{124}$Te(p,n)$^{124}$I, $^{127}$I(p,5n)$^{123}$Xe, $^{127}$I(p,3n)$^{125}$Xe, $^{82}$Kr(p,2n)$^{81}$Rb, $^{nat}$Kr(p,x)$^{81}$Rb, $^{124}$Xe(p,2n)$^{123}$Cs, $^{124}$Xe(p,pn)$^{123}$Xe, $^{203}$Tl(p,3n)$^{201}$Pb, $^{203}$Tl(p,2n)$^{202m}$Pb, $^{203}$Tl(p,4n)$^{200}$Pb.

The collected data sets were analysed again and a new selection was made. From the newly selected data groups a single coherent data set was composed. An updated, recommended excitation curve produced, by fitting the selected set using the cubic spline statistical fitting method. The updated recommended data were verified and validated using independent experimental thick target yield data. The collected experimental yield data were critically compared with integral thick target yields deduced from the new recommended cross sections.

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## [178] Measurement of the neutron flux in the 1 MW Pb-Bi liquid target of the MEGAPIE project

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The MEGAwattPIlot Experiment at the Paul Scherrer Institute, Switzerland, will be the first experimental demonstration of feasibility for a long term operation of a "realistic" liquid Pb-Bi spallation target irradiated under a 1 MW (590 MeV, 1.7 mA) proton beam. During one year target operation, we plan to measure the components of the neutron flux generated in this innovative spallation target.

To achieve this goal, 8 micro fission chambers will be inserted in the central rod of the target to measure thermal, epi-thermal and fast components of the neutron flux. As thermal component of the flux will be measured with U235 deposit detectors, epithermal neutrons will be detected using 250 micro meter Gadolinium shielded detectors and fast neutrons will be probed with threshold fission detectors (Pu242 and U238). These neutron detectors, that have been designed to stand high intensity neutron fluxes ($> 10^{14}$ n/s/cm$^2$), will allow to monitor time and space variations of the neutrons flux at the level

of 1%, giving thus access to an integral validation of neutron generation and transport models. The impact on the neutronic balance of spallation residuals inside the liquid target will be also evaluated.

New types of fission chambers have been thus recently developed to stand the high (600°C) and frequent (T=200°C every 20 mn) temperature variations together with the strong mechanical end electromagnetic constraints expected all along the irradiation of the MEGAPIE target. We will present their characteristics and the results obtained in term of signal accuracy, background sensibility, and electromagnetic shielding after integral tests performed at the Institute Laue-Langevin of Grenoble (France).

In parallel to neutron flux measurements, two detectors will be dedicated to the study of transmutation of Am241 and Np237 in the intense (1.7 $10^{14}$ n/s/cm$^2$) and 40% moderated neutron spectrum of the MEGAPIE spallation target. The online monitoring of the fission rates for those minor actinides will experimentally answer on the incineration potentials of various systems presenting similar neutron spectra (Molten salt reactors, GTMHR,...)

These challenging measurements should provide the scientific community with a set of experimental data which will allow to assess the neutronic performances of what could be the future generation of high intensity neutron sources dedicated to ADS.

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## [182] Residual Nuclide Production by Proton-Induced Reactions on Uranium for Energies between 20 MeV and 70 MeV

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Within the HINDAS project, proton irradiation experiments were performed at the injector cyclotron of the Paul Scherrer Institute at Villigen/Switzerland in order to investigate the production of residual nuclides from natural uranium. The stacked-foil technique was used to cover proton energies between 20 MeV and 70 MeV. Copper targets were used for monitoring the proton beam using the reaction Cu-65(p,n)Zn-65. Residual radionuclides were measured by off-line gamma-spectrometry. Excitation functions were obtained for the production of Y-91, Zr-95, Nb-95m, Mo-99, Ru-103, Pd-112, Cd-115, Sb-124, Sb-126, Sb-127, Te-132, I-131, Cs-134, Cs-136, Cs-137, Ba-140, Ce-141, Ce-144, Nd-147, and Np-238. The experimental data are compared the sparse results of earlier measurements and with theoretical excitation functions calculated by the newly developed TALYS code. Good agreement between theory and experiment was obtained for product masses up to 115. For higher mass fission products and for Np-238 there are still systematic deviations between theory and experiments. These deviations are discussed as deficits of the fission model in the heavy part of the fission product distribution.

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## [186] From the HINDAS project: Excitation functions for residual nuclide production by proton-induced reactions

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The results reported here were obtained by proton irradiation experiments with classical kinematics. These investigations are complimentary to those using inverse kinematics where the primary residuals can be studied in detail at certain energy points. Experiments with classical kinematics are restricted to residual nuclides with usually at least a few hours' half-lives, but allow studying the complete excitation functions from thresholds up to the highest energies. For proton-induced reactions, our experiments aimed to further developing and completing the cross section database which was established by our collaboration in recent years. It was extended to the heavy target elements Ta, W, Pb, and Bi for energies up to 2.6 GeV. In addition, new measurements for the target element iron were performed up to 2.6 GeV. For the target element lead, a comprehensive set of excitation functions published recently was completed by AMS-measurements of cross sections for the production of the long-lived radionuclides Be-10, Al-26, Cl-36, and I-129 and by mass spectrometric measurements of for stable and radioactive rare gas isotopes of He, Ne, Ar, Kr, and Xe. Residual nuclide production from natural uranium was investigated for energies from 21 MeV to 69 MeV. Comprehensive tests of the nuclear reaction codes TALYS and INCL4+ABLA, which were developed within the HINDAS project, were performed with the new experimental results for the target elements Fe, Ta, W, Pb, Bi, and U for the entire energy range.

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## [192] Excitation Functions of Helion Induced Nuclear Reactions for the Production of the Medical Radioisotope $^{103}$Pd

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The radionuclide $^{103}$Pd is of considerable medical interest. It has a half-life of 17 d and decays almost exclusively by EC. The emitted X-rays and Auger electrons are ideally suited for internal radiation therapy, especially for treatment of prostate cancer. For the production of $^{103}$ Pd, several methods have been reported. However, to date the $^{103}$Rh(p,n)$^{103}$Pd reaction is most commonly used. In the present work we studied the hitherto uninvestigated helion induced reactions on enriched isotopes of ruthenium. Excitation functions of the nuclear reactions $^{100}$Ru($\alpha$,n)$^{103}$Pd, $^{101}$Ru($\alpha$,2n)$^{103}$Pd, $^{101}$Ru($^3$He,n)$^{103}$Pd and $^{102}$Ru($^3$He,2n)$^{103}$Pd were measured using the stacked-foil technique in combination with non-destructive high-resolution X-ray spectrometry. Thin (2-5 mg·cm$^{-2}$) metallic samples of highy enriched ruthenium isotopes $^{100}$Ru, $^{101}$Ru and $^{102}$Ru were used as targets in the irradiation of the stacks with 27 MeV $^4$He and 36 MeV $^3$He ion beams at the compact cyclotron CV28 of the Forschungszentrum Jülich GmbH.

The excitation function of the reaction $^{100}$Ru($\alpha$,n)$^{103}$Pd has a bell like form and the maximum cross section value lies around 500 mb at 17-18 MeV bombarding energy. The cross section of the $^{101}$Ru($\alpha$ ,2n)$^{103}$Pd reaction increases sharply with the increasing incident $\alpha$-particle energy and reaches a high value of $\sim$1100 mb at 23 MeV. The integral thick target yield of $^{103}$Pd calculated from the excitation function of the ($\alpha$,n)-reaction amounts to 960 KBq/$\mu$Ah at 25 MeV and that from the ($\alpha$,2n)-reaction to 1050 KBq/$\mu$Ah at 23 MeV.

The excitation function of the reaction $^{102}$Ru($^3$He,2n)$^{103}$Pd shows the maximum cross section value ($\sim$300 mb) at the incident energy of 17-18 MeV and has a high energy tail with values 30-40 mb, while the $^{101}$Ru($^3$He,n)$^{103}$Pd reaction has a constant cross section of about 10 mb over the whole incident energy range studied. This behaviour is in accordance with the known systematic observation for such kind of reactions. The thick target yields of $^{103}$Pd calculated for the last two reactions amount to 725 KBq/$\mu$Ah and 50 KBq/$\mu$Ah, respectively, at 34 MeV $^3$He ion energy. So from the investigated reactions the reaction $^{101}$Ru($\alpha$,2n)$^{103}$Pd may be considered to be the most suitable. In comparison to the presently used the (p,n)-reaction, however, the yield via the ($\alpha$,2n)-reaction is by a factor of 8 smaller.

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## [195] NUCLEAR REACTION DATA FOR IBA APPLICATIONS

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Main aspects are discussed concerning nuclear reaction cross-sections for PIGE analyses, especially referring to cultural heritage diagnostics, within the framework of ion beam analysis (IBA) methods, also reviewing main results from recent international Conferences on Nuclear Data for Science and Technology and from NEA-NSC meetings and IAEA initiatives on the matter. In particular, within the frame of an overall summary on nuclear data requirements for IBA applications, main needs are pointed out specifically referred to the PIGE diagnostics purposes of present interest. Particularly, nuclear data relevant to light-element analysis in archaeometry are specifically considered and their impact on the knowledge and conservation of the cultural heritage is pointed out, especially discussing most significant examples concerning the beneficial use from the evaluated nuclear data on the results obtained by the application of this nuclear analytical technique. Consistently, relevant topics are discussed concerning the evaluation of the requested nuclear reaction data, on the basis of the existing experimental values and nuclear model calculations, according to the appropriate parameterisation and the consequent effects on the calculation results. Particularly, theoretical models on the nuclear structure and for estimation of the nuclear level densities are discussed, such as the modern algebraic models and the microscopic superfluid models, with emphasis on their influence on the calculations of photon production data, especially referring to the effects on the semi-empirical level density formula normally adopted in cross-section calculations, mainly to the parity-breaking effects and to the dependence of the most crucial level density parameter on the nuclear excitation energy. Accordingly, recent results are presented as obtained for (p,x$\gamma$) reaction data, by comparing critically selected experimental data and the relevant model calculations, with regard to significant isotopes of low- and medium-mass elements of actual interest when considering alloys and other fabrication techniques for ancient manufacts.

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## [199] Comparison Between Experimental Data and Model Calculations of Excitation Functions for Production of Radionuclides for Metabolic Radiotherapy and PET

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The radioisotope production for medical applications has been brought up in the years at INFN LASA Laboratory. Mainly scientific aspects applications have been investigated concerning radiation detection and relevant instruments, the measurements of excitation functions of the involved nuclear reactions and the requested radiochemistry studies. Concerning the related nuclear data evaluations, based on model calculations and critically selected experimental data, the appropriate competence developed at ENEA Division for Advanced Physics Technologies has been implemented in this work. The EMPIRE-II code is adopted following an inter-comparison with previous ENEA codes.

A series of high specific activity accelerator-produced radionuclides in no-carrier-added (NCA) form, for uses in metabolic radiotherapy and for PET, are investigated, such as:

1. NCA $^{64}$Cu, produced by $^{nat}$Zn(d,axn) and $^{nat}$Zn(d,2pxn) reactions for simultaneous positron/negatron metabolic radiotherapy and PET, together with the short-lived radionuclide for PET imaging $^{61}$Cu;
2. NCA $^{66}$Ga, high-energy positron emitter (4.2 MeV) for metabolic radiotherapy and PET;
3. $^{186g}$Re, produced by $^{186}$W(p,n) and $^{186}$W(d,2n) reactions for bone metastases pain palliation by negatron(1.1 MeV) metabolic radiotherapy and SPECT imaging;
4. NCA $^{211}$At/$^{211}$Po, produced by $^{209}$Bi($\alpha$,2n) reaction, with internal spike of gamma emitter $^{210}$At from $^{209}$Bi($\alpha$,3n) reaction (and small amount of $^{210}$Po as radiotoxic long-lived impurity), for high-LET radiotherapy and immunoradiotherapy;
5. NCA $^{225}$Ac/$^{213}$Bi/$^{213}$Po, in-vivo nano-generator for high-LET radiotherapy and immunoradiotherapy.

In this work, new revised measurements and model calculations are presented for excitation functions of $^{nat}$Zn(d,X)$^{61,64}$Cu,$^{66}$Ga reactions, referring to irradiation experiments at K=38 Cyclotron at JRC-Ispra. Concerning the reaction data for producing $^{186g}$Re and $^{211}$At/$^{211}$Po (including significant emission spectra) and $^{210}$At, the most recent and critically selected experimental results are discussed, in comparison with model calculations paying special care to pre-equilibrium effects estimate and to appropriate overall parameterisation. Only model calculations are presented for $^{226}$Ra(p,2n)$^{225}$Ac reaction, in lack of extremely difficult measurements.

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## [200] Projectile and Target Fragmentation in the Interaction of $^{12}$C and $^{27}$Al

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Most of the studies involving the interaction of light nuclei were performed at incident energies well below 10 MeV/amu where mean field processes together with particle evaporation are able to describe the data. Above 10 MeV/amu, however, nucleonic degrees of freedom become increasingly important. The need for a better understanding of the predominant reaction mechanisms regarding the interactions of light nuclei at these energies is further stimulated by the increasing number of applications e.g. in hadron therapy with carbon beams.

Previous studies of Intermediate Mass Fragments (IMFs) emitted in the interaction of $^{12}$C and $^{16}$O with medium to heavy mass nuclei at incident energies of some tens of MeV/amu have convincingly demonstrated that the IMFs can originate from two unrelated mechanisms: binary fragmentation of the projectile and nucleon coalescence. In the case of two light nuclei this scenario may change. If it is assumed that fragments emitted from this interaction are due in part to projectile and in part to target fragmentation, a significant dependence on the entrance channel of the c.m. fragment yield in the forward and backward direction is to be expected.

Angular distributions of the emitted IMFs ($4 \leq Z \leq 14$) were measured in $^{27}$Al on $^{12}$C as well as in the inverse reaction at incident energies corresponding to a c.m. excitation energy of 108 MeV. Double differential cross sections of the inclusive IMF spectra are compared to model calculations, which include the direct breakup as well as nucleon coalescence. These results indicate the relative importance of projectile and target breakup contributing to the IMF spectra at small and large scattering angles, respectively.

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## [225] Development of a nuclear reaction database on silicon for simulation of neutron-induced single-event upsets in microelectronics and its application

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The radiation effects known as single-event upsets(SEUs) in microelectronics have recently been recognized as a key reliability concern for current and future silicon-based integrated circuit technologies. Cosmic-ray neutrons having a wide energy range from MeV to GeV are regarded as one of the major sources of the SEUs in the devices used on the ground or in airplanes. Therefore, nuclear reaction data to describe the interaction of neutrons with the nuclides contained in the devices are highly requested as a fundamental physical quantity necessary for understanding the SEU phenomena and estimating the SEU rate. To meet this demand, we have recently developed a cross section database for silicon, using evaluated nuclear data file (JENDL-3.3, JENDL-HE, and LA150) and QMD calculation, for neutron energies ranging from 2 MeV to 3 GeV. Using the cross section database and the energy loss calculation of secondary ions, one can simulate the initial SEU processes, namely generation of secondary ions via nuclear reactions and initial charge distribution induced in the device. In the present work, a simple device structure with only silicon layers is taken into account, and the SEU cross sections are calculated on the basis of the initial processes simulated in terms of a Monte Carlo method. Two major parameters, the sensitive volume and the critical charge of the device, are included in the calculation. We have analyzed the experimental data for SRAMs and the other simulation result for DRAMs using this model calculation. It is shown that the dependence of SEU cross sections on incident neutron energy is reproduced satisfactorily by adjusting the two parameters. Through these analyses, we investigate the secondary ions generated by nuclear reactions with Si and the incident energy range which have the most important impact on SEUs. The sensitivity of the nuclear reaction data on SEUs is also discussed.

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## [226] Cross-section sensitivity analysis for the water-cooled lithium lead test blanket module in ITER-FEAT

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The differential operator perturbation technique implemented in the three-dimensional Monte Carlo radiation transport code MCNP-4C has been applied to the EU water-cooled lithium lead (WCLL) test blanket module (TBM) integrated in ITER-FEAT in order to assess changes in some parameters due to changes in nuclear cross section data.

The TBM uses Li17Pb83 as a tritium breeder with 90

Sensitivity profiles and integral sensitivities of tritium production rate for partial cross sections of Pb, Fe and 6Li have been obtained. Relatively small sensitivities to the cross sections considered have been observed.

Sensitivity profiles of radiation damage responses (He, H production) in iron and chromium isotopes to their own cross sections (direct contribution) show that the sensitivity is concentrated in the higher (13.5–14.5 MeV) energy region where high ($> 1$) sensitivity is found. Calculations of sensitivity to important transport cross sections are in progress.

An examination of the provided sensitivity profiles will aid to identify the most important energy ranges for the cross sections under study. Combined with covariance data the sensitivity profiles help to indicate which reaction cross sections and energy ranges need additional measurements and evaluations in order to satisfy the design parameters criteria.

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## [229] Application of fusion power reactor to transmute minor actinides from spent nuclear fuel

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The work presents calculation analysis of dual-aimed Fusion Power Reactor (FPR) application for minor actinides transmutation and energy production simultaneously. Arrangement of long-life minor actinides (Np, Am, Cm) was proposed in the assemblies of FPR blanket which has modular configuration and surrounded Deuterium-Tritium plasma with 14.1 MeV neutron source. Blanket also contained lithium material for Tritium production and self-supplying the fusion reaction in plasma. Several FPR blanket compositions were considered in order to obtain optimum on three reactor parameters: transmutation rate of actinides, tritium breeding, power production. Tritium breeding ratio (TBR) was obtained at level 1.11 for water-cooling and reached up 1.56 in variant with helium-cooled assemblies with Np nitride. It was concluded that rows with actinides from processed waste fuel should be arranged near the plasma First Wall (FW). Transmutation calculations show that isotope Np-237 has 14 % burnout per full power year (FPY). Effective neutron-multiplication factor Keff in the reactor can be low (0.3–0.7) which fully excludes a possibility of uncontrollable power rise during in the reactor operation.

FPR possesses an inherent safety and it has a neutron abundance source for waste transmutations. Major parameters of waste assemblies and rods were taken similar to those of operating LWR to minimize guesses on effectiveness of other technologies. While considered neptunium oxides, nitrides and metallic compositions from processed spent nuclear fuel of fission reactors it was stated advantages of NpN.

Method for three-dimensional activation analysis of fusion reactor materials was used in transmutation calculations. MCNP neutron/photons three-dimensional transport and FISPACT inventory codes are used for optimization of minor actinides burn-up and tritium production rate in the blanket. Thermohydraulic and thermomechanic calculations are done by ANSIS code. Results show that nuclear heat deposition in waste fuel rods does not exceed the heat deposition in fuel elements of existing LWR.

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## [245] Determination of the $^{99}$Tc(thermal $n$,$\gamma$)$^{100}$Tc reaction cross section from the prompt $\gamma$-ray yields

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The $^{99}$Tc is one of the most important long-lived fission product nuclides (half-life: $2.1 \times 10^5$ y) contained in radioactive nuclear wastes, and is suggested as a candidate for the transmutation of the wastes using neutron-capture reactions because the reaction-product nuclide $^{100}$Tc decays to the stable nuclide $^{100}$Ru with a half-life of 15 s. To examine the possibility of the transmutation, it is essential to know precise values of the reaction cross section.

Several authors have measured mainly through activation methods the cross section for thermal neutrons, which are scattered in a range between 16 b and 24.3 b: there's a tendency that the old ones scatter around 20 b and the new ones close to 24 b, and the trend is reflected to the evaluated nuclear data sets.

The purpose of the present work is to determine thermal neutron capture cross section of $^{99}$Tc from the yields of prompt gamma rays to the ground state of $^{100}$Tc, by analyzing previously obtained experimental data which remained unanalyzed.

The $(n,\gamma)$ data had been obtained at the Los Alamos National Laboratory Omega West Reactor by one of the authors and other collaborators. An enriched sample of $^{99}$Tc (100 %, 84.6 mg, in metallic form) was placed in the thermal column of the internal target facility of the reactor. The target position was 1.5 m from the edge of the reactor core. At this position, the thermal neutron flux was $\sim 6 \times 10^{11} n\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and the Cd(In) ratio is $\approx 2000$.

Gamma-ray spectra were obtained with a 30-cm$^3$ coaxial intrinsic Ge detector positioned inside a 20-cm-diameter by 30-cm-long NaI(Tl) annulus which is optically divided into two halves. The Ge detector was located 6.3 m from the target and was operated either in the Compton-suppressed (CS) mode (0.388 keV/channel) or in the pair-spectrometer (PS) mode (0.629 keV/channel). The pulse-height analyzer had 16384 channels, and in the PS mode, gamma rays with their energies below 11.3 MeV were measured.

Energy calibrations were performed with the prompt $\gamma$-ray spectrum from neutron capture in melamine ($C_3H_3N_6$) in the PS mode, and with the prompt $\gamma$ ray from the $^1$H$(n,\gamma)$ reaction plus the annihilation radiation in the CS mode. Efficiency calibrations in the CS mode were done with a set of standard radioisotopic sources with precalibrated $\gamma$-ray intensities, while in the PS mode the efficiency curve was derived from the relative intensities of $\gamma$ rays from the $^{14}$N$(n,\gamma)$ reaction. The cross sections are normalized to the recommended value of $\sigma_\gamma(2200\ \mathrm{m/s}) = 332.6 \pm 0.7$mb for $^1$H.

Peak-area analysis was done for each gamma ray observed both in the CS and the PS modes, and the energy as well as the intensity was determined. Combining the results of the analyses in both modes, the data were obtained of about 1100 gamma rays emitted in $^{99}$Tc(thermal $n,\gamma)^{100}$Tc reaction. From the obtained data, with the help of the previously reported information on the levels of $^{100}$Tc, a partial decay scheme was constructed. Among the observed gamma rays, six were assigned to transitions to the ground state, namely 172-, 223-, 264-, 341-, 356- and 459-keV ones. From the intensities of these ground-state transitions, corrected for internal conversion, the (lower limit of the) cross section is obtained as $21.37 \pm 0.62$ b.

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## [256] LWR Fuel Cycle with Reduced HLW Production

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Advanced fuel cycle of light water reactor VVER-440 (Russian design) with inert matrix fuel is described. Cycle is based on combined fuel assemblies containing standard uranium pins and transmutation pins with transuranium elements from spent fuel in inert matrix. This cycle is compared with standard open fuel cycle based on radially profiled assemblies and with standard closed fuel cycle containing MOX fuel assemblies. Numerical analysis is based on spectral code HELIOS. Cycle performance indicators covering waste stream parameters and risk connected with spent fuel are evaluated.

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## [262] Excitation functions and production rates of radionuclides produced in the proton bombardment of Pr and La

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The excitation fuctions of 17 radionuclides produced in the interaction of protons with $^{141}$Pr have been measured from threshold up to 100 MeV. For this purpose stacks of Pr foils were irradiated followed by off-line gamma-ray spectroscopy with a calibrated HPGe detector system. For the interaction of protons with $^{139}$La, similar activation measurements were performed up to an incident energy of 20 MeV.

The main interest of these measurements is to optimise the production of the radionuclides $^{139}$Ce and $^{139}$Pr. The single strong 166 keV gamma line of $^{139}$Ce (half-life of 137.6 days) makes it an ideal calibration source for SPET equipment. The optimum target configuration for its production is a tandem target with Pr in the higher-energy slot and La in the lower-energy slot. The radionuclide $^{139}$Pr partially decays by positron emission and finds application in PET. It can be used to label human serum albumin (HSA) which allows the quantifying of the metabolism of tumours. This study investigates its production via the precursor $^{139}$Nd, which can be radiochemically separated from the Pr target matrix.

The measured data are compared with theoretical hybrid model predictions by means of a recent version of the code ALICE-IPPE.

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## [264] Reich-Moore Analysis of the Iodine-127 and Iodine-129 Resolved Resonance Range

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The surge of interest for the transmutation of nuclear waste has triggered a significant demand for improved neutron cross-section data for minor actinides and long-lived fission products. With 400 kg of $^{129}$I produced yearly in the reactors of the EU countries and a very long $\beta$- half-life of $1.57^7$ years, iodine requires disposal strategies that will isolate this isotope from the environment for long periods of time. Therefore, $^{129}$I is potentially a key long-lived fission product for transmutation applications, since $^{129}$I transmutes in $^{130}$I after a single neutron capture and decays to the noble gas $^{130}$Xe with a 12.36 h half-life.

Very little experimental work have been performed on iodine-129 neutron cross sections because of sample procurement and handling problems. The recommended resonance parameters available in the European (JEFF3.0) and Japanese (JENDL3.3) neutron libraries were generated from the capture resonance area given by R.L. Macklin. The JEFF3.0 and JENDL3.3 databases contain parameters for 126 resonances up to 3 keV. In each evaluation, the resonances are assumed to be s-waves. New accurate iodine-129 capture cross section data in the Resolved Resonance Range would help to reduce uncertainties in waste management concepts.

For that purpose, Time-Of-Flight measurements covering the [0.5 eV-100 keV] energy range have been carried out at the 150 MeV pulsed neutron source GELINA of the Institute for Reference Materials and Measurements (IRMM, Geel, Belgium). Two types of experiments have been performed, namely capture and transmission experiments. They are respectively related to the neutron capture and total cross sections. Since the $PbI_2$ samples used in this work contain natural and radioactive iodine, extensive measurements of $^{127}$I have been carried out under the same experimental conditions as for the $^{129}$I. The data reduction process was performed with the Analysis of Geel Spectra system (AGS), and the resonance parameters were extracted with the SAMMY and REFIT shape analysis codes. The Resolved Resonance Range has been analysed in terms of Reich-Moore parameters up to 10 keV: 719 and 400 resonances have

been identified respectively for $^{127}$I and $^{129}$I. Average parameters have been determined from the present set of resolved resonance parameters with the help of the ESTIMA code. The latter relies on Bayes' Theorem to provide a confident s-wave sample. It uses also the Porter-Thomas integral distribution method to determine accurate s-wave average spacing and neutron strength function by accounting for missing levels. In a last step, the present iodine-127 and iodine-129 resonance parameters have been converted into ENDF-6 format for the future release of the European neutron library JEFF3.1.

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## [270] Evaluation of reaction cross section data used for thin layer activation technique

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Thin layer activation (TLA) is a widely used nuclear method to investigate and control the loss of material during wear, corrosion and erosion processes. The process requires knowledge of depth profiles of the investigated radioisotopes produced by charged particle bombardment. The depth distribution of the activity can be determined with direct, very time-consuming step by step measurement or by calculation from reliable cross section, stopping power and sample composition data. These data were checked experimentally at several points performing only a couple of measurements.

As part of the results and conclusions of the IAEA Co-ordinated Research Programme on "Thin layer activation method and its application in the industry" a database was reported in the final Technical Document, containing TLA profiles and relevant cross sections for 35 reactions induced by p, d, $^{3}$He and alpha-particles on 12 different elements. Later a computer program package was developed using this database published in the CRP Technical Document.

In the last decade a systematic investigation on charged particle induced nuclear reactions on metals was in progress at the Debrecen Cyclotron Laboratory for different applications in collaboration with other cyclotron laboratories and with the IAEA, including systematic cross-section measurements, data compilations and evaluations.

Activity-depth distribution functions are also frequently deduced from the obtained evaluated cross sections and compared with the directly measured calibration curves or other calculated curves published in the literature. We found significant disagreements between the result of the published values and our results and other reported data. It is difficult to find the reason of the disagreements between the directly measured and the calculated values because of the lack of initial parameters for the directly measured values, which are usually not fully published. In case of calculated TLA curves (like data in TECDOC) the initial parameters are well defined (and reported) therefore the comparison was possible.

To clarify the disagreements between our calculated data with those deduced from the TLA database we decided to investigate the possible reasons for the disagreements. Concerning that the accuracy of stopping power calculations is significantly higher than the accuracy of the corresponding cross section data, we compared first the recently published recommended cross section data with those in the basic input data file of the TLA database.

The systematic comparison showed significant disagreements in many cases. The results will be presented and the possible reason of the disagreements will be discussed. The improvement and extension of the TLA database is proposed with extended list of the candidate reactions based on more recent evaluated data.

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## [280] Excitation functions for production of $^{88}$Zr and $^{88}$Y by proton irradiation of Nb and Mo

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Yttrium-88 is produced in large scale for investigation of the biodistribution of $^{90}$Y labeled therapeutic compounds, for gamma-ray detector calibration source and for dose determination in accelerator technology. Y-88 could be obtained by high energy spallation reaction on Mo and by medium energy reaction (up 100 MeV) on Mo and Nb. The $^{88}$Y could be produced directly or via generator system

from $^{88}$Zr. No cross section data available practically for these medium energy reactions. The excitations functions of $^{nat}$Mo(p,x)$^{88}$Zr,$^{88}$Y and $^{nat}$Nb(p,x)$^{88}$Zr,$^{88}$Y were measured up to 70 MeV by using stacked foil irradiation technique and off-line gamma ray spectroscopy of the products. $^{nat}$Al(p,x)$^{22,24}$Na and $^{nat}$Cu(p,x)$^{56,58}$Co,$^{62,65}$Zn monitor reactions were to characterize the beam intensity and the energy degradation. Model calculations were done by using the Alice IPPE code to compare with the experimental values and to extrapolate the production cross sections up to 100 MeV. The model calculations reproduce well the experimental data. Integral yields of $^{88}$Zr and $^{88}$Y radioisotopes as a function of bombarding energy were calculated by using the experimentally measured excitation functions (up to 70 MeV) and by using the theoretical cross sections (normalized to the experimental data at the overlapping energy range). The expected thick target yields of $^{88}$Zr and $^{88}$Y for total degradation of 70 MeV protons on Nb target are 790 MBq/C and 120 MBq/C are respectively. The similar yield data of $^{88}$Zr and $^{88}$Y on Mo target are significantly lower: 1.55MBq/C and 0.2 MBq/C. On the basis of the yield data it can be concluded that from the point of view of the production yields the Nb+p route is much more efficient. The extension of the experimental data measurement up to 90 MeV is in progress.

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## [282] Excitation functions of proton induced reactions on $^{nat}$Sn: relevance to the production of $^{111}$In and $^{114m}$In for medical applications

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The $^{111}$In is used both for diagnostic and therapeutic purposes. The 114mIn is a therapeutic radioisotope. The production possibility of the medically used $^{111}$In and $^{114m}$In were investigated via proton irradiation of tin targets by determining the excitation functions, production yields and the impurity levels. According to our knowledge no earlier results are available in this energy range in the literature. The aim of investigation of this route was to avoid difficulties with commonly used, expensive, highly enriched targets ($^{111}$Cd, $^{112}$Cd, $^{113}$Cd, $^{114}$Cd). The excitation functions for production of $^{111mg,114m,117m}$In radioisotopes were measured from 30 up to 70 MeV by using activation method, stacked foil irradiation technique and direct HpGe gamma counting of irradiated samples. The irradiations were done at an external beam line of Tohoku University cyclotron. The beam intensity and the energy degradation were controlled in the whole energy range by simultaneously measured $^{nat}$Al(p,x)$^{22,24}$Na and $^{nat}$Cu(p,x)$^{56,58}$Co, $^{62,65}$Zn monitor reactions. Theoretical excitation functions for $^{nat}$Cd(p,x)$^{111,114,117}$In reactions have been calculated using the well developed Alice-IPPE code. The measured experimental results were compared with the yields obtained earlier for other high energy alternative production routes (by using Cd and In targets with natural isotopic composition or by using highly enriched Cd targets).

According to our results to production of high purity $^{111}$In for diagnostic purposes is possible only through the decay of $^{111}$Sn via chemical separation of the directly produced indium radioisotopes after EOB. For therapy only a mixture of $^{111}$In and $^{114m}$In radioisotopes can be produced effectively by proton induced nuclear reactions on natural tin target.

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## [283] Neutron Production in Spallation Reactions of 600-2000 MeV protons on Thick Lead Target - comparison of experiment and MCNPX simulations

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Accelerator Driven Transmutation Technologies stand a good chance to become an alternative to the permanent storage of the spent nuclear fuel. The transmutation is assumed to be done by intensive neutron field produced by the spallation reactions of relativistic protons on heavy element target. Several Monte Carlo simulation codes are claiming to be able to describe the course of spallation reaction and transport of produced particles in thick target. The purpose of this study is to test reliability of their

prediction by comparison with experimental data about spatial distribution of neutrons produced both in simple and in complex systems of target, uranium and surrounding moderator irradiated with relativistic energy proton beam.

We analysed three experiments carried out by us at the accelerators of JINR Dubna, Russia. The beams of relativistic protons (660 MeV, 885 MeV, 2 GeV) strike the massive cylindrical lead target (diameter 9.6 cm, length 50 cm). The distribution of the produced neutron field was deduced from the activation detectors (foils of Al, Cu, Au and Bi) placed on the surface of and near to the target. Finally we made comparison of experimentally deduced yields with Monte-Carlo based simulations performed with the MCNPX code and couple of LAHET (version 2.7) and MCNP4B code.

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## [287] Transmutation of $^{238}$Pu, $^{239}$Pu, $^{237}$Np, $^{241}$Am, $^{129}$I Using Neutrons Produced in Target-Blanket System "Energy & Transmutation" Bombarded by Relativistic Protons

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Target-blanket facility "Energy & Transmutation" was constructed in LHE JINR laboratory to study neutron spectra parameters and transmutation potential of subcritical reactor coupled with spallation neutron source. Blanket consists of natural uranium fuel rods with about 200kg amount of uranium. In the center of the blanket there is massive spallation target made from Pb. Target is irradiated by protons from the LHE Nuclotron accelerator with integral intensity approx. 1E14 protons. The radioactive samples for transmutation studies are placed on the top of the blanket with a set of activation threshold detectors to determine neutron spectra. Reaction (transmutation, fission) rates of various isotopes produced in radioactive transuranium samples and $^{129}$I, $^{127}$I samples as well as threshold detectors (Au, Al, Cu, Ni, Co, Ta, In, Bi) analysis are determined using nuclear gamma-spectroscopy methods. HPGe detectors of LNP JINR perform gamma spectra measurements. Measurements of gamma spectra starts approximately two hours after irradiation and samples are measured more than week, so it is possible to find out isotopes with half-lives from about one hour to about a month. Gamma spectra are analyzed used standard spectroscopy methods included various kinds of corrections taken into account. Total number of protons is establishing from aluminum beam monitors, an estimation neutron spectrum is composing from threshold detectors results, and reaction rates (per one proton and per one target's atom) of residual nuclei found are determined. Computation analyses will be performed, computed and experimentally determined spectra of neutron are compared. Fission products yields observed are compared with database data taken from various available nuclear data libraries and with older experimental data. Project "Energy & Transmutation" is supported by ISTC (project number 1372).

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## [290] Transmutation of radioactive nuclear waste - present status and requirement for the problem oriented nuclear data base. Approach to scheduling the experiments (reactor, target, blanket).

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Starting from the middle of the 80-s there have been a lot of activity worldwide, USSR/Russia included, in developing of Nuclear fuel cycle and its proper components acceptable for transmutation of long-lived nuclear wastes. Different options are considered: fission reactors with thermal and fast spectrum, including special reactor-transmuters, blanket of fast reactors. Each of these options has both attractive features and complex problems.

New NFC is developing in Russia with features of minimized dangerous of the wastes directed for final burial. The NFC is based on fast power reactors with transmutation of the main part of its own RAW. Subcritical blankets may be used at the end stage of the nuclear energy.

Blankets of accelerator driven transmuters as well as fusion machine received significant national and international attention. Being subcritical, these facilities need in intensive neutron source: target of high energy proton accelerator or thermo-nuclear plasma The main feature attributed to accelerator-driven transmuters is an essential broadening in the nucleon energy of primary neutrons (up to 1 GeV) compared to traditional fission reactor. Concerning their fuel composition, it is worth to emphasize that subcritical mode of operation gives an opportunity to burn out large amounts of minor actinides.

Due to the facts that irradiated compositions (minor actinides and some extracted fission products) are not traditional fuel material, and irradiate conditions, are unusual, particularly in accelerator target and blanket.

Transmutation as a goal of irradiation arise specific to accuracy of nuclear data for isotopes — candidates for transmutation, which essentially differ from requirements, used for traditional fuel cycle.

As the matter of the fact that there is lack of reliable nuclear data for both minor actinides, fission products and structural materials in the energy region both over traditional reactor energies (0 – 10 MeV), for area of essentially higher energy (up to 1 GeV and even higher).

In addition to that, designing the spallation target brings about essentially new engineering problems associated with accumulation in situ various spallation products which have not been of concern in traditional nuclear power technology.

It seems reasonable that general urge towards principal improvement of NFC through transmutation technologies provoked among others numerous attempts to measure and evaluate nuclear data with proper quality. Therefore the ISTC sponsored impressive list of the projects focused on measurement of nuclear data for transmutation or/and processing available data into cross-section files and libraries.

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## [291] Measurement of differential thick target neutron yields (TTY) from Fe, Cu(p,n) reactions at 35, 50 and 70 MeV

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Differential thick target neutron yields (TTY) data are required for the design of accelerator shielding and the accelerator-based neutron sources. Data are required to be obtained with high energy resolution over wide energy range and range. In the present experiments, we obtained the TTY data for the $^{nat}$Fe, $^{nat}$Cu(p, xn) reaction at 35, 50 and 70 MeV. These elements are very popular element for beam-lines and beam-dumps in accelerators. Therefore, it is important to know secondary neutron spectra these elements bombarded by accelerated charged particles. The experiment was carried out as apart of the TTY series of measurements using a time-of-flight (TOF) technique at the Cyclotron and Radioisotope Center, Tohoku University (CYRIC) with the K=110 AVF cyclotron and the beam-swinger system. Data were obtained by using two gain detectors with different flight path length (3.5m and 11.0 m) to cover almost entire range of secondary neutrons at several laboratory angles between 0- and 110-deg. Neutron detectors were NE213 detectors and the bias for low energy measurements was ∼0.5 MeV. Neutron events were separated from gamma-ray events by the pulse-shape-discrimination (PSD) technique, and its efficiency was obtained with the Monte Carlo code SCINFUL-R. The data obtained were corrected for the attenuation by air and the target.

The results were compared with other experiment and the LA-150 data library. The data for copper at 70 MeV are in good agreement with those by Meigo, but show marked disagreement with LA-150 in higher energy range. This tendency is similar to other heavy nucleus such as tungsten and tantalum which were measured before by us. We are planning to do measurements for thin target to clarify the difference.

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## [296] Nuclear Data for Multiple Prompt Gamma-ray Analysis

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Most of nuclei emit two or more prompt gamma rays simultaneously in the neutron capture reaction. In MPGA, the prompt gamma rays are simultaneously measured by two or more sets of gamma ray detectors, these gamma rays are reconstructed in the pair of two prompt gamma rays, and it is added to the two dimensional spectrum which sets two axes as the energy for every events. The gamma-ray distribution corresponding to the pair of the gamma ray which are emitted simultaneously will be obtained. By analyzing this two-dimensional gamma-ray peak, resolution can be raised by leaps and bounds. MPGA needs not only the knowledge of energies of capture gamma-rays, but also nuclear structure data. While the energies are usually accurate, many of the excited level structures are of poor knowledge. Complete sets of these nuclear data are of great importance. New MPGA system will be constructed at the guide-hall of JRR-3M in Japan Atomic Energy Research Institute. This system consists of three Clover Ge detectors with anti-compton suppressor. The absolute efficiency of the system is about 10% for 1.3 MeV gamma-ray. It will be widely used in the fields of agriculture, engineering, geosciences, environmental science and so on.

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## [308] $^{232}$Th (n,$\gamma$) $^{233}$Th Thermal Reaction Cross Section Measurement

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The thermal neutron capture cross section of the $^{232}$Th(n,$\gamma$)$^{233}$Th reaction was experimentally obtained. This work was motivated by the IAEA Coordinated Research Project on Evaluated Nuclear Data for Thorium-Uranium Fuel Cycle. The irradiations were performed at the IPEN IEA-R1m 2MW pool research reactor. The targets consisted of $\sim$ 15 mg of high purity metallic Thorium (Reactor Experiments Inc., USA). The thermal and epithermal neutron fluxes were monitored with the $^{197}$Au(n,$\gamma$)$^{198}$Au reaction with a pair of Au-Al alloy foils with and without cadmium cover placed with the sample in each irradiation. The neutron fluencies were determined using the Westcott formalism. The reaction yields were determined from the residual gamma-ray activity, measured with an HPGe detector (35 % efficiency), calibrated with a standard $^{152}$Eu source. The detector efficiency was fitted by the least-square method applying covariance analysis to all uncertainties involved. The obtained result for $\sigma_{th}$ was 6.23 $\pm$ 0.20 b and for $\sigma_0$ , 7.19 $\pm$ 0.20 b. These results were compared with previous measurements and evaluations.

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## [316] Evaluation and Calculation of Elastic Scattering Cross Sections for Ion Beam Analysis

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The needs of the Ion Beam Analysis (IBA) community in charged particle nuclear data are reviewed. There are different IBA methods based on registration of elastically scattered particles or the products of nuclear reactions and a reliable source of cross section is needed for all of them except for Rutherford backscattering for which the cross section can be calculated according to the known formula. To provide charged particles cross sections for IBA is a task that resembles the problem of nuclear data for the majority of other applications in all respects save one - differential cross sections rather than total ones are needed for IBA. The present status of the nuclear data for IBA is analyzed. The problems which should be resolved in order to establish a reliable basis for the IBA analytical work are discussed.

Recent results obtained in the evaluation of proton elastic scattering cross sections for magnesium and sulphur and for $^4$He scattering from oxygen are presented. The present status of the SigmaCalc software

developed for the IBA scientists having no expertise in nuclear physics to perform the calculations of the required differential cross sections is discussed. The ways to provide the IBA community with a reliable source of nuclear data are outlined.

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## [320] Reactor Production of Thorium-229

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The rapidly increasing interest in the clinical applications of bismuth-213 coupled with the limited availability of thorium-229 necessitate investigation of alternative production routes for Th-229, Ra-225 and Ac-225. Currently, U-233 is the only viable source for high purity Th-229, however, the anticipated growth in demand for Ac-225 may soon exceed the levels of Th-229 present in the aged U-233 stockpile. It is estimated that only ~38 g or ~8 Ci of Th-229 can be extracted from entire U-233 stockpile, which is only 80 times the current ORNL 229Th stock. Considering the rather low annual production rate of Th-229 from U-233 (0.92 mCi/kg) and increasing difficulties associated with the U-233 safeguard, routine processing of U-233 is presently unfeasible. The alternative routes for the production of Th-229, Ra-225 and Ac-225 include both reactor and accelerator approaches. Th-229 can be produced from neutron transmutation of Ra-226 and Ra-228 targets [Appl.Radiat.Isot., 49, 345 (1998)]. The theoretical production yields are hampered by the lack of neutron capture cross-section data of the intermediate radionuclides. Using conservative values for the unknown cross sections, the yield of Th-229 is on the order of 0.02 mCi per mg of Ra-226 for a 100-day irradiation at a neutron flux of $2\times10^{15}$ $n\cdot s^{-1}\cdot cm^{-2}$, with a thermal to epithermal ratio of 20. Note that under these conditions, the amount of Th-228 and Ac-227 contaminants which are co-produced with Th-229 are 4000 and 70 times larger, respectively. Nevertheless, even from a mixture of Th-228 and Th-229, high purity Ac-225 can be obtained from the mixture by initially extracting Ra from Th and then extracting Ac-225 from the Ra mixture (Ra-224, the daughter of Th-228, alpha decays to Rn-220 with no $\beta$-decay to Ac-224). Recycling the Ra-226 target will theoretically result in an increase in the yield of Th-229 due to the formation of Ra-228.

The results of two irradiations at the Hydraulic Tube Facility of ORNL High Flux Isotope Reactor (HFIR) will be presented. In these experiments, targets were 33.5 and 330 mg of Ra-226 and were irradiated for one and three reactor cycles (~24-d cycle) , respectively.

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## [325] Production cross-sections of some radionuclides with therapeutic applications

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We have performed reaction model calculations to evaluate nuclear cross-sections of radionuclides with therapeutic applications, as part of a Coordinated Research Project sponsored by the International Atomic Energy Agency (IAEA). More specifically, we calculate the production cross-sections for the $^{90}$Y producing reactions, $^{89}$Y(n,$\gamma$)$^{90}$Y and $^{90}$Zr(n,p)$^{90}$Y, and the capture reactions $^{187}$Re(n,$\gamma$)$^{188}$Re, $^{152}$Sm(n,$\gamma$)$^{153}$Sm, $^{124}$Xe(n,$\gamma$)$^{125}$Xe and $^{102}$Pd(n,$\gamma$)$^{103}$Pd.

The calculations were performed using the computer codes EMPIRE-II, available at I.A.E.A., and TNG, from Oak Ridge National Laboratory (ORNL). The global spherical optical model of Koning and Delaroche was used for neutrons and protons and the McFadden-Satchler spherical optical potential was used for alphas. We analyse the various possible level density formalisms and make specific comparisons of the results of the two codes for all different cases. For high energies, the fully degenerate multistep compound emission of neutrons and protons and the multistep direct scattering of the incident neutron were taken into account. Different methods are used in TNG and EMPIRE-II to implement this multistep pre-equilibrium process, which makes this comparison particularly interesting to reveal the strengths and possible deficiencies of both codes. As far as possible, the level densities were adjusted to the available discrete states.

The calculations were compared to the experimental data available in the EXFOR library and with previous evaluations in the ENDF formatted libraries.

We have also evaluated unshielded spectrum averaged cross sections for the above reactions using the ENDF formatted libraries, which are discussed at the end of this work.

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## [336] Measurement of the neutron capture cross section of $^{232}$Th at the CERN-nTOF facility

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The interest in high resolution neutron capture cross section data has gained much interest in recent years due to the development of new activities related to nuclear energy, like the transmutation of nuclear waste, the thorium-based nuclear fuel cycle and accelerator driven systems (ADS).

The amount of nuclear waste, notably the higher actinides, can be reduced by using a fuel cycle based on $^{232}$Th. The isotope $^{232}$Th by itself is not fissile but after neutron capture followed by $\beta$-decay, the fissile isotope $^{233}$U is formed. The build-up of the higher actinides, especially americium and curium, is strongly suppressed due to the lower atomic and mass number of thorium.

The recent renewed interest in the nuclear fuel cycle based on $^{232}$Th/$^{233}$U has made clear that the existing knowledge of reaction cross sections for many of the relevant isotopes is still rather poor. For an optimized design of a thorium-cycle based accelerator driven system (ADS) an improved knowledge of these isotopes is crucial.

We have measured the neutron capture cross section of $^{232}$Th at the newly constructed neutron time-of-flight facility at CERN. Neutrons are created by spallation reactions induced by a pulsed, 6 ns wide, 20 GeV/$c$ proton beam with up to $7 \times 10^{12}$ protons per pulse, impinging on a 80x80x60 cm$^3$ lead target. A 5 cm water slab surrounding the lead target serves as a coolant and at the same time as a moderator of the initially fast neutron spectrum, providing a wide energy spectrum from 0.1 eV to about 250 MeV with a nearly $1/E$ flux dependence between 1 eV and 1 MeV.

The high instantaneous neutron flux, high resolution and low background make this facility well suited for high quality neutron cross section measurements. In particular neutron capture measurements on radioactive isotopes or low mass samples take advantage of the enhanced signal to background ratio as compared to other existing facilities.

The main characteristics of the facility will be described as well as the used capture setup with $C_6D_6$-based gamma-ray detectors associated with a pulse height weighting technique. The measured reaction yield has been analyzed within the $R$-matrix modelization of the reaction and the resonance parameters have been extracted up to a few keV. From the resonance information the level density information, including a missing-level correction, has been extracted. Above this energy in the unresolved resonance region the capture cross section is presented as point-wise data up to about 500 keV and the neutron strength functions have been fitted from the data.

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## [342] The Experimental Determination of the Spectal Indices R-28 and D-25 Inside of the Fuel Pellet of the IPEN/MB-01 Reactor

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It has been having a great deal of effort related to the U-238 resonance absorption of thermal reactors ( see `http://www.nea.fr/lists/ueval` for details). New libraries have been generated at Los Alamos and at Oak Ridge and several benchmark calculations are under way. It has also been recognized the need of new experiments. The main purpose of this work is to present the measurements performed at the IPEN/MB-01 research reactor facility related to the determination of the spectral indices R-28 ( ratio of the epitherma to thermal neutron captures in U-238) and D-25 ( ratio of the epithermal to thermal fissions in U-235). The measurements are realized in the assymptotic region and inside of the fuel pellets with foils whose diameter is less than those of the fuel pellets. A mathematical model is being employed to correct for the cadmiun perturbations and for the transformation of the measured data into a thermal cutoff of 0.625 eV. MCNP-4C is being used for such a task and also for the final three dimensional results. The final results shows that a good agreement is achieved for the U-235 case for several libraries. However, for the U-238 case ( R-28) much work still has to be devoted since the

calculated results are unpredicted when compared to the experimental ones. The recent improvements of the Keff comparison reported by several works at the ueval page related to the the new U-238 release ( ornl2) may not have the proper support when the spectral indices are considered. A complete analysis is still going on at IPEN and a detailed description will be given in the final paper.

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## [344] A New Experimental Approach for the Experimental Determination the Spectal Indices R-28 and D-25.

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It has been having a great deal of effort related to the U-238 resonance absorption of thermal reactors ( see `http://www.nea.fr/lists/ueval` for details). New libraries have been generated at Los Alamos and at Oak Ridge and several benchmark calculations are under way. It has also been recognized the need of new experiments. The main purpose of this work is to present a new approach for the measurements of the spectral indices R-28 ( ratio of the epitherma to thermal neutron captures in U-238) and D-25 ( ratio of the epithermal to thermal fissions in U-235). The measurements are realized in the assymptotic region of the IPEN/MB-01 reactor facility. The proposed method does not require any sort mathematical corrections needed for the cadmiun perturbations and even for the transformation of the measured data into a thermal cutoff of 0.625 eV. The proposed method is based on a gamma scanning technique of the fuel rod. Such a apparatus has a opening collimator of 1.0cm. The methodology considers an experimental fuel rod where it is chosen two positions along its axial directions whrere the reaction rates are symmetrical. One posiiton is kept bare while the another one is covered with a sleeve of specified size and thickness of cadmiun. This cadmiun sleeve position is chosen such that it does not perturb the opposite bare axial position. The gamma spectrometry countings are performed alternately in the bare position and in the central region of the cadmiun covered position. From the photopeak countings of Np-239 and Ce-143 one can infer the reaction rates of U-238 and U-235. In the case of U-235 there is some corrections due to the U-238 fissions. The cadmiun ratio is taken conversely for each of the reaction rates considered in this work. The final results shows that a good agreement is achieved for the U-235 case for several libraries. However, for the U-238 case ( R-28) much work still has to be devoted since the calculated results are unpredicted when compared to the experimental ones. The recent improvements of the Keff comparison reported by several works at the ueval page related to the the new U-238 release ( ornl2) may not have the proper support when the spectral indices are considered. A complete analysis is still going on at IPEN and a detailed description will be given in the final paper.

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## [349] Estimation of secondary neutron dose in proton therapy using multicollisional and Pauli-blocking constrained Monte Carlo calculations

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Neutrons contribute to dose deposition in critical organs outside the irradiated target volume. However, the literature regarding neutron dose from proton therapy is limited. This issue is of special relevance for young patients, particularly when life expectancy is long.Previous estimates have been based mainly on calculations using the FLUKA code[1,2]. In this work we have used a quite sofisticated multi-collisional Monte Carlo code (MCMC), developed in our group, which takes into account Pauli-blocking effects in a novel and more precise way[3]. Thus we have obtained spectra and multiplicities for neutrons emitted in the reactions: p+C, p+O, p+Ca and p+N, for proton energies from 100 to 200 MeV. When compared to the ICRU evaluation[4], our results show a slight shift of the spectra towards higher energies, and neutron multiplicities a factor of $\sim 2$ smaller. This is somewhat expected, since a more rigorous Pauli-blocking constrain favours higher energy states and restricts the number of available exit channels. Because neutron delivered doses are proportional to average neutron multiplicities, estimates that didn't

take properly into account Pauli-blocking effects may have greatly overestimated the dos outside the target. Therefore, we suggest tha the risk from secondary neutrons may be lower than originally assumed, while reccomending further verification.

The art of cancer treatment is findig the right balance between tumor control and injury to normal tissues[5].

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## [351] Sensitivity of Activation Cross Sections of Tungsten to Nuclear Reaction Mechanisms

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Tungsten is a material widely used in fusion technology. The radioactivity induced in tungsten by D-T fusion neutrons is relevant to safety aspects and to waste management of power plants. A benchmark experiment with pure W irradiated by 14 MeV neutrons showed for several of the dominantly produced radionuclide ratios of calculated-to-experimental activity (C/E) that were significantly above unity [1,2], when calculated with the European Activation System (EASY). In order to reduce the deviation of C from E a detailed analysis of the activation cross sections was carried out using the computer codes EMPIRE-II and TALYS as well as local parameter sets within the STAPRE-H code. The consistent input-parameter set in the last case and the independent data used for its determination and validation are presented. There include the optical model potentials, the corresponding neutron-resonance data, neutron total cross sections, proton reaction cross sections, the low-lying level and resonance data involved for determination of the level density parameters within the realistic approach recently developed. In addition the $\gamma$-ray strength functions $f_{E1}(E_\gamma)$ which are used for the calculation of the $\gamma$-ray transmission coefficients and the corresponding capture cross sections are also presented. The recent measurements [3] of the neutron total cross sections for the $^{182,183,184,186}$W isotopes were in particular used in an analysis of the deformed optical potential within the coupled-channels model to provide the neutron transmission coefficients in the entrance channel. Finally, the sensitivity of the calculated cross sections to various model parameters is derived and discussed in connection with improving the C/E of the benchmark experiment.

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## [368] Radiotoxicity and Risk Reduction of TRU Elements from Spent Fuel by Transmutation in the Light Water Reactor

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A conventional PWR of type VVER-440 operating in a sustainable advanced fuel cycle mode with complete recycling of TRU elements in an Inert Matrix Combined Fuel Assembly (IMC-FA) in the same reactor was investigated. A preliminary assessment and the differences between various nuclear fuel

cycles in terms of the risk analysis and its indicators has been conducted. The results indicate that the sustainable advanced fuel cycle option can, for the same amount of energy generation, significantly reduce both the amounts and radiotoxicity of the spent nuclear fuel in comparison with the conventional once-through $UO_2$ or MOX fuel cycles.

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## [384] Neutrino Energy Spectra from Nuclear Reactor Calculated from Nuclear Data Libraries

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Nuclear reactors generate a highly intense flux of electron-antineutrinos from fission-products through beta-minus decay, and a slight amount of electron-neutrinos through either beta-plus decay or electron capture. Neutrino energy spectra are usually calculated by the beta-decay theory. Since the reactor neutrinos are emitted from a great number of nuclides, the calculation requires a lot of level scheme of these nuclides. Nuclear data libraries, however, are available these days. It is possible to evaluate the electron-antineutrino and -neutrino spectra for a nuclear reactor on the basis of nuclear data libraries (JENDL-FP-Decay-Data-File-2000, JENDL-3.3). JENDL-FP-Decay-Data-File-2000 is a data library evaluated in Japan.The library contains the decay data of 1229 FP nuclides from A=60 to 178, and includes decay data of half-lives, decay modes, Q values, branching ratios and average energy values of such radiations as beta-rays, gamma-rays and alpha-rays. In addition, spectral data on individual radiations including conversion electrons and X-rays are separately given in the library. To compute neutrino spectra, we used the beta-rays spectra of this data library. Unlike the case of antineutrinos, electron-neutrinos often have monochromatic spectra caused by electron capture (E.C.). We calculated these spectra with the Q values of E.C. The main fissile nuclides to yield FPs in a reactor are U-235, U-238, Pu-239 and Pu-241. For FP yields of these nuclides, cumulative FP yield data for the thermal neutron (0.025eV) fission are selected in JENDL-3.3. These spectrum-data and yield-data enable us to readily compute the neutrino and antineutrino spectra from a reactor. In the study, we derive electron-neutrino and -antineutrino spectra in the energy range of 10 keV to 8 MeV from nuclear data libraries. The method gives good agreement with other studies for electron-antineutrino spectra. We show the simple method to estimate reactor neutrino spectra without complicated computation.

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## [393] Damage induced by a proton beam in an iron window evaluated from recent GSI

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For hybrid reactors, one of the critical points is the window between the accelerator (where the intense proton beam is produced under vacuum) and the spallation target inside the subcritical reactor. Actually, it is a barrier between the reactor and the accelerator. The important question to know, up to which extent the accelerator will have to be included in the last safety barrier rely on the detailed knowledge of its resistance under extreme conditions.

The beam will induce heat deposition and nuclear reactions leading to the accumulation of new chemical species which could be responsible for a loss of cohesion of alloy and embrittlement of the window. Furthermore, damages will occur because of atom displacements due to the recoiling nuclei produced by the spallation process.

The favorite materials proposed by metallurgists are ferro-martensitics steels (T91 or EM10) with about 90

These numbers will be presented and compared to calculations performed with an old spallation model (Bertini-Dresner) and with a recent one (INCL4-ABLA) showing to which extent one can rely on them for this type of predictions in this region of target mass.

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## [401] Importance of nuclear data for windowless spallation target design

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Accelerator driven systems consist of an accelerator delivering a proton beam to a spallation target that in turn couples to a sub-critical nuclear reactor. In the case of the MYRRHA concept, the spallation target considered is a liquid lead-bismuth target without window interface between the beam line and the spallation target. This concept avoids frequent replacement of the target and improves the spallation performances but will need special attention to secondary particles emitted with large angle and to volatile spallation products.

Preliminary calculations have shown that the rather high dose reached at the top shielding of the sub-critical core seems to be underestimated when the calculated spallation spectrum at large angle are compared to the experimental ones. The accurate evaluations of the flux levels are important to determine the doses and the activation rates around the beam line.

Various products, emitted directly by spallation reactions or indirectly due to the high temperature reached in the liquid target, can evaporate and stream to the beam line. The design of the recovery system need to evaluate carefully the production of volatile spallation products. To this aim, the distribution of heat generated in the target must be well calculated. This distribution will also allow to assess the impact of the density variation to the neutron source distribution.

In this paper we will deal with the importance of nuclear data needed to estimate accurately the level of radiation around the beam line and of volatile spallation products. Obviously, these aspects have direct implications on radioactive waste management and operational control of the spallation source. The assessments will be performed with the help of the MCNPX code compared to experimental measurements.

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## [409] Sensitivity and Uncertainty Analysis to Burn-up Estimates on ADS Using ACAB Code

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For detailed ADS design calculations the burn-up uncertainty estimates due to activation cross section uncertainties are important. We applied the sensitivity-uncertainty analysis to burn-up calculations in a lead-bismuth cooled subcritical Accelerator Driven System. Sensitivity-uncertainty methods provide a method to identify the nuclear cross sections and the dominant chains that contribute most significantly to the isotopic inventory. These uncertainty estimates are valuable to assess the need of any experimental re-evaluation. In this work, activation cross-section uncertainty data are taken from the FENDL and EAF2003 libraries.

ACAB code has the capability to perform a comprehensive sensitivity-uncertainty analysis in activation calculations. This procedure is based on a first order Taylor series approach, and in the use of original algorithms to compute efficiently the partial derivatives. Sensitivity coefficients of nuclide concentrations to reaction cross sections are obtained and then combined with the uncertainty information to calculate uncertainty estimates of the isotopic inventory. This methodology is found practical for providing the uncertainties of the different inventory response functions due to the uncertainties of each of the reaction cross sections separately. The most important limitation of the method is that it is impractical to deal with the synergetic/global effect of the uncertainties of the complete set of cross sections. To overcome this limitation, an uncertainty analysis methodology based on Monte Carlo has been implemented in ACAB. The Monte Carlo procedure is based on simultaneous random sampling of all the cross sections involved in the problem. The probability distributions of isotopic inventory (and estimate of the confidence level) are obtained with Monte Carlo method. We have also identified the critical cross sections and we evaluate the effect of a reasonable reduction in the uncertainties of the cross sections in order to obtain a reasonable reduction in this uncertainty.

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## [410] State of activation cross section uncertainties and their effect on fusion applications.

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Errors in activation calculations have been obtained considering the activation cross sections uncertainties included in the latest available nuclear data libraries, assuming the neutron environment in the ITER vacuum vessel.

The most relevant cross sections and corresponding uncertainties regarding isotopic concentration limits for hands-on and remote recycling, and shallow land burial have been identified. The methods used to determine these uncertainties, based either on theoretical models or experimental data evaluations, have been analyzed.

When the uncertainties are extracted from theoretical models such as systematics, graphical information or estimates, their values may vary from less than one percent to a factor of five. Here, we consider these errors as acceptable and only in some critical reactions the need of experiments is proposed. In those cases when the experimental data have been used, a study of the experimental data library EXFOR has been developed and new uncertainty values have been proposed. The comparison between results using these new values and those considering the original uncertainties is very useful in the quality assessment of activation data libraries and shows the need for new cross sections measurements and evaluations.

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## [419] Computed Induced Activities for Trace Element Concentration of Human Blood Serum by 14-MeV Neutrons

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Human blood serum constitutes traces of the following elements: chromium, manganese, iron, nickel, copper, zinc, selenium, bromine and lead. The induced activities per gram per unit flux, when performing appropriate reactions for the isotopes of the prementioned elements, have been computed using about 14-MeV neutrons induced primary reaction cross-sections. These cross-sections are done using the computer code Exifon which is based on an analytical model for statistical multistep direct and multistep compound reactions. The agreement between the computed cross-sections and the available experimental data is fairly good. The induced $\beta$ or $\gamma$ activities for the $(n,p)$ and $(n,\alpha)$ reactions for the isotopes of the prementioned elements with half-life-times of residual nuclei ranging from few seconds to several hundreds of years, per gram per unit neutron flux have been computed.

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## [446] Study of external neutron source for accelerator driven system by General-Purpose Particles and Heavy Ion Transport Monte Carlo code PHITS

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Recently, accelerator-driven subcritical system (ADS) has been studied as a useful neutron source for partitioning and transmutation of minor actinides. A subcritical core of ADS is driven by external neutron source (S), which is generated by the spallation reaction. Although S will be suffered from the changes of the core parameters such as coolant void generation, in previous study, the changes are not taken into account for an analysis of ADS. In the present study, we studied the effects to S of the following core parameters; Incident proton energy (0.5GeV 2.0GeV), beam diameter (0∼10cm), void generation in target (0%∼50%), void generation in coolant region (0%∼70%), and the level position of target surface (25cm). The calculations in this study were performed by General-Purpose particle and heavy ion transport Monte Carlo code PHITS, which has been developed at JAERI and Tohoku University based on NMTC/JAM. An ADS core of U-Pu-MA fuel and Pb-Bi coolant was employed for the analysis in the present study.

As the results, the following effects to S by the changes of the core parameters was observed.

1.Energy change: the change exceeds factor10 and the distribution of S in the ADS core was almost the same in shape.

2.Beam diameter: the difference of S was within 10% and the distribution of S was almost the same.

3.Void generation in target region: the change of S was factor3 at the maximum and the distribution was changed especially for z direction.

4.Void generation in coolant region: the effect was within 50% and the distribution changed largely.

5.target level: the difference was factor 2 and the distribution was varied very large.

It is found that the effects of the core parameter to S are very large in magnitude and shape. The S variation for dynamics behavior and core performance of an ADS should be considered in an ADS study.

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## [469] Study on Response Function of Organic Liquid Scintillator for High-energy Neutrons

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Liquid organic scintillators, such as the NE213 and BC501A, have been widely used for neutron spectrometry based on time-of-flight (TOF) or unfolding method in the energy region above several MeV. This is because these scintillators have a comparatively high detection efficiency and a good capability to distinguish neutrons and gamma-rays.

Response function of liquid organic scintillators is essential to derive the accurate neutron spectrum. Therefore, many experiments to measure the response function were performed in the incident neutron energies below 100 MeV. Experimental data above 100 MeV, however, are very scarce because of the difficulty to produce the mono-energetic neutron beam in this energy region. The existing Monte Carlo codes, SCINFUL and CECIL, are often used for estimation of the response function instead of the experimental data. These codes are known to reproduce well the response function for incidences below 100 MeV. Unfortunately, the codes are not applicable to the calculation in the higher energy region. To determine the response function for incidences above 100 MeV, some problems remain still unresolved.

In order to meet these requests, a new Monte Carlo code, designated as SCINFUL-QMD, has been developed. In this code, QMD model is employed as a high-energy nuclear reaction model to extend the upper limit of incident neutron energy to 3 GeV. In the comparison with the experimental data up to 800 MeV, the validation of SCINFUL-QMD was confirmed. The results of SCINFUL-QMD agreed with the experimental data better than those of other calculation codes. To obtain more precise predictions, some further modifications are required to estimate the deposition energy and scintillation light in more detail.

In addition, we will plan to perform measurements of the response function of liquid organic scintillator for neutron incidences up to 1 GeV at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) of National Institute of Radiological Sciences (NIRS), Japan. A comparison between our experimental data and SCINFUL-QMD will be shown at the conference.

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## [471] Activation experiment at KUCA for establishing an experimental facility of Accelerator Driven Subcritical Reactor

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The present work is for the on-going project to establish an experimental reactor facility for Accelerator Driven Subcritical Reactor (ADSR) at Kyoto University Reactor Research Institute (KURRI). This experimental facility mainly consists of a 150 MeV accelerator and a critical assembly. The accelerator is a Fixed Field Alternating Gradient (FFAG) accelerator and will be newly installed for this project. The critical assembly is the existent Kyoto University Critical Assembly (KUCA). Our paper will describes the details of the project; the development plan of the project, the descriptions of the experimental facilities, the experimental issued and so on.

To establish this facility by employing the existent critical assembly, many experiments are required for modifying, revising and adjusting a critical assembly to match the new accelerator and to perform an ADSR experiment. Our paper will describe those experiments in details.

As a typical example of those experiments, this abstract describes an activation experiment to survey efficient method to conduct neutrons to a core of KUCA since a neutron target has to be placed outside a core. In the experiment, a D-T source by an existent accelerator was employed and a neutron target was placed at a reflector region outside a core. Several collimators especially designed for a KUCA core were placed between a core and the neutron target, and Indium wires were located beside the collimator for activating Indium wires and for measuring the In(n,n') activity distributions. From the comparison of the results for different collimators, it is confirmed that the numbers of neutrons induced into a core are largely influenced by the size of collimator, and the appropriate collimator is found. The collimator is very helpful for increasing neutrons induced to a core. Including these experiments, our paper will be described about a lot of experiments performed for the new KURRI facility to perform effective experiments for ADSR.

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## [474] Experimental Study of Integral Data of BFS Fast Critical Assembly with Lead Coolant

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So as the analysis of the experiments has shown that the use of neutron data from files of various national libraries results in significant differences in the calculated values of basic neutronic characteristics, a series of critical assemblies at the BFS facility was created for the validation of the neutron data for Pb and Bi in fast reactor spectrum [1].

The experimental program aimed to the measurements of the integral parameters such as spectral indices, capture in uranium vs. fission of plutonium, central coefficients of reactivity, void effect of coolant was carried out on BFS-77 critical assembly. This assembly was the benchmark type model of BREST-300 reactor (mixed nitride fuel, lead coolant, BR for the core of $\approx 1$ ). The results of the experiments, so as the assembly description prepared for the analysis.

Calculations of the measured parameters are carried out using Russian calculation codes and the most modern versions of nuclear data libraries (ABBN-93, ENDF/B-6, JENDL-3.2 etc.).

Calculation benchmark models of the experiment are constructed. They are used for testing of precise (with detailed description of geometry and neutrons transition) and engineer (with homogeneous core description and diffusion theory of neutrons transition) neutron physics codes and integral neutron data. Correction factors necessary to adequate comparison with the measurements are obtained for a simpler model and their uncertainty are estimated. Corresponding recommendations on their uncertainties and/or correction will be worked out.

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## [475] Experimental Study of Minor Actinides Data at BFS Fast Critical Assembly with Metal Fuel

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The problem of refining of minor actinides (MA) fission cross-section and, especially, MA capture cross-section is rather actual, since at present their uncertainties are several times more than it is required. The BFS-73-1 critical assembly was the benchmark model of KALIMER design, based upon uranium metal fuel less then 20% enrichment and sodium coolant and represented the specific class of neutron spectrum in long-time IPPE MA programme investigations [1]. Several most important MA representatives (Np-237, Am-241 and Am-243) were studied on BFS-73-1. The experiments involved fission cross-section ratios of Np-237, Am-241 and Am-243 to Pu-239; Np-237 capture to Pu-239 fission cross-sections ratio; Np-237 samples central reactivity coefficients normalized to U-235 or Pu-239. The results of the experiments, so as the assembly description prepared for the analysis.

Calculations of the measured parameters are carried out using Russian calculation codes and the most modern versions of nuclear data libraries (ABBN-93, FOND-2.2, ENDF/B-6, JEF-2.2, JENDL-3.2 etc.).

Calculation benchmark models of the experiment are constructed. They are used for testing of precise (with detailed description of geometry and neutrons transition) and engineer (with homogeneous core description and diffusion theory of neutrons transition) neutron physics codes and MA neutron data. Correction factors necessary to adequate comparison with the measurements are obtained for a simpler model and their uncertainty are estimated. Corresponding recommendations on their uncertainties and/or correction will be worked out.

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## [550] CZT based Handheld Radionuclide Identifier, "radFINDER"

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A new generation of HHRIID's (Handheld Radionuclide Identification Device) for nuclear material safeguards, for nuclear inventory monitoring, for advanced warning systems and for illicit trafficking of radioactive materials smart and portable gamma spectrometers are needed. The standard handheld gamma spectrometers for such applications use NaI scintillation detectors or small CZT semiconductor detectors for gamma spectrometry and single He-3 counters or LiI(Eu) detectors for the detection of neutrons. Such detectors have their limitations especially for the identification of shielded special nuclear materials because of their relatively poor energy resolution or because of their small volume/efficiency.

Using digital signal processing (DSP) combined with improved spectrum analysing software programs and very promising new detector developments a new generation of portable hand held gamma spectrometers, the so-called *radFINDER* was developed.

The *radFINDER* integrates multi-channel analyser, amplifier, high voltage power supply, and powerful embedded computing with unique detectors for gamma and neutron radiation. As gamma radiation detector multiple CZT detector elements are implemented. Whereas large volume CZT segments are used for search and source finding functions smaller CZT crystals with excellent energy resolution will acquire gamma ray spectra. The detection of neutron presence in the radiation field is based on multiple high pressure He-3 tubes with polyethylene as moderator. The paper describes the technical parameters of the individual components. The spectroscopic characteristics will be described in detail.

The automatic nuclide identification is based on advance template matching which allows to uniquely determine shielded nuclear material. The built-in library consists of about 75 nuclides and nuclide combination templates. The paper describes the identification method and process in detail.

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