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Book of Abstracts

Fission ExperimentS and Theoretical Advances

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Conference Program

Fission Activities at LANSCE

Robert C. Haight

Los Alamos Neutron Science Center, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The Los Alamos Neutron Science Center (LANSCE) provides intense, pulsed beams of neutrons that are used to investigate the physics and to supply nuclear data of neutron-induced fission over a wide range of incident neutron energies from sub thermal to 100s of MeV. Recent and on-going experiments include the measurement of fission cross sections; x-rays, gamma-rays and neutrons emitted promptly in the fission process; mass and charge yields of the fission products; and total kinetic energy released, all as functions of incident neutron energy. Specialized detector systems, developed to focus on specific experimental observables, include the GEANIE and DANCE arrays of gamma-ray detectors, the two Chi-Nu arrays of neutron detectors, the Time-Projection Chamber (TPC) and the SPIDER detectors for fission fragment detection and characterization. More conventional ionization and solid state detectors are also employed. This talk will give an overview of the experimental program with illustrations from selected measurements. Monte Carlo modeling of the neutron and gamma-ray transport in the experimental environment is essential to the interpretation of the data for several of these measurements. Data taken at LANSCE will be compared with data reported in the literature and with ENDF evaluations. The experiments are carried out by researchers from Los Alamos and other laboratories.

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Recent and Future Research Activities on Nuclear Fission at n_TOF

Nicola Colonna

Istituto Nazionale Fisica Nucleare - Italy

Since more than a decade, an important contribution in studies of nuclear fission is being provided by the neutron time-of-flight facility n_TOF at CERN. Measurements on several long-lived major and minor actinides, from ^{232}Th to ^{245}Cm, have been performed so far, mostly related to nuclear technology. New, high accuracy data are in fact needed in order to improve safety and efficiency of current reactors, as well as to develop advanced systems for energy production and waste transmutation, such as Gen IV fast reactors, Accelerator Driven Systems and reactors based on innovative fuel cycles.

The main features of the n_TOF facility, that make it well suited for measurements of fission reactions, are the wide energy range, the high instantaneous neutron flux and the very low repetition rate. Furthermore, in the first experimental area, located at 185 m from the spallation target, the high resolution in neutron energy allows to better characterize and extend the Resolved Resonance Region. The convenient features of the neutron beam have been complemented over the years with high-performance detection systems. In the first part of this talk an overview of the results on fission cross section and Fission Fragment angular distribution, obtained so far at n_TOF, will be presented.

To further expand the potentiality of the facility, a second experimental area (EAR-2) at the shorter flight path of 20 m has recently been built. The increased flux, in combination with the shorter time-of-flight, results in a further reduction of the background related to the natural radioactivity of the sample, thus allowing to measure radioactive isotopes with half-lives as short as a few years. Furthermore, samples of very small mass, of the order of ?g, can be measured in EAR-2, thanks to the high flux. Fission studies on short-lived actinides, such as ^{232}U, ^{238}Pu and ^{244}Cm, are now being planned at EAR2@n_TOF. In the second part of the talk, the main features of the second experimental area will be presented, together with the foreseen experimental program on nuclear fission.

Measurement of the ^{242}Pu(n, f) cross-section at the CERN n_TOF facility

Andrea Tsinganis

Dep. of Physics, National Technical University of Athens

The accurate knowledge of relevant nuclear data, such as the neutron-induced fission cross-sections of various plutonium isotopes and other minor actinides, is crucial for the design of advanced nuclear systems as well as the development of comprehensive theoretical models of the fission process. The ^{242}Pu(n, f) cross section was measured at the CERN n_TOF facility taking advantage of the wide energy range (from thermal to GeV) and the high instantaneous flux of the neutron beam. The results are presented along with a detailed description of the experimental setup, Monte-Carlo simulations and the analysis procedure.

Neutron-induced fission cross sections for U-233,234,236,238 up to 200 MeV

Fredrik Tovesson[1], A. Laptev[1], T. Hill[2]

[1] Los Alamos National Laboratory, PO 1663, Los Alamos, NM 87545, USA

[2] Idaho State University, 1999 Alvin Ricken Road, Pocatello, ID 83201, USA

Nuclear data plays an important role in the performance of fission-based technologies. Fission cross sections of actinides are of particular relevance and in some cases needs to be known with very high accuracy. Sensitivity studies of various nuclear reactor types have shown the need for fission cross sections with less than 5% uncertainty for several minor actinides, especially for fast spectrum reactors.

The Los Alamos Neutron Science Center (LANSCE) provides a unique facility for studying nuclear data over the full range of neutron energies of interest to science and applications. The unmoderated spallation target at LANSCE-WNR provides a neutron spectrum from 100 keV to hundreds of MeV, while the moderated target at LANSCE-Lujan Center is used for measurement from about 200 keV down to sub-thermal energies. At both targets the time-of-flight method is used to determine the incident neutron energy. The fission cross sections of four uranium isotopes have been measured at LANSCE-WNR using a parallel plate ionization chamber relative to the U-235(n,f) standard. The measurement covers incident neutron energies of 0.1-200 MeV and total uncertainties are around 3%. The results are compared to previous measurements and current evaluations.

Nuclear fission as resonance-mediated conductance

George F. Bertsch

Department of Physics, University of Washington, Seattle WA 98195, USA

Up to now, the theory of nuclear fission has relied on the existence of a collective coordinate associated with the shape of the nucleus, giving rise to a spectrum of channels through which the fission takes place. We present here an alternate formulation of the theory, in which the fission is facilitated by individual states in the barrier region rather than channels over the barrier. In a simplified limit, the theory reduces to a well-known formula for electronic conductance through resonant tunneling states. Qualitatively, the resonance-mediated theory is supported by the observation of large-scale fluctuations in the transmission function at energies above the fission barrier. In contrast, the channel-based theory predicts monotonically increasing transmission functions at those energies.

Self-consistent adiabatic description of the fission : automatic production of class-II PES

Noël Dubray

CEA, DAM, DIF, F-91297, Arpajon, France

Our description of the fission process relies on the production of static, adiabatic potential energy surfaces (PES). This production is a non-trivial procedure, because of three main technical problems : convergence issues, hysteresis, and discontinuities. In this presentation, we define and explain the origins of these problems, and propose a way to automatically get rid of two of them (convergence and hysteresis), and to identify and localize the last ones (discontinuities) at the PES production level (not at the post-production stage). We finally explain how this enables us to claim that the resulting class-II PES are reproducible and do not depend on the production procedure. More importantly, quantities such as saddle points extracted from a local class-III PES are true saddle points and are said to be 'final', since they will not change when increasing the deformation space.

Microscopic Calculations of Fission Barriers in the Actinide Region

M. H. Koh, L. Bonneau, P. Quentin, H. Wagiran

[1] Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[2] University of Bordeaux, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Chemin du Solarium, F-33175 Gradignan, France
[3] CNRS-IN2P3, Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Chemin du Solarium, F-33175 Gradignan, France

The information of the fission barrier heights are important to the fission cross section calculation in that a slight variation in the barrier height could alter the fission cross section significantly.

Although much effort has been made in the study of fission barrier of even-mass nuclei, microscopic study of odd-mass nuclei has been relatively few. One reason for the lack of such study was due to the complication brought upon by the breaking of the time-reversal symmetry in a system with odd number of identical particles (fermions). A proper microscopic description would entails that the effect of the time-reversal symmetry breaking to be accounted for, self-consistently.

We proposed to study in such a manner, the fission barrier heights of some actinide nuclei using the Hartree-Fock (HF) method supplemented with the particle-number conserving, Highly Truncated Diagonalization Approach (HTDA) for the treatment of pairing correlations.

The HTDA study was undertaken to circumvent the basic deficiency of the usual Bardeen-Cooper-Schrieffer (BCS) method whereby the inappropriateness of the BCS approach is associated with the lower single-particle density near the Fermi level, hereby brought about due to the blocking of the single-particle state by the unpaired nucleon.

The focus of the work will be on the fission barrier heights of the odd-mass nuclei and the band-head spectroscopy at the ground state, top of the first barrier and isomeric well.

Why the finite element method could be a powerful tool to model fission dynamics

David Regnier

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

During the past decades, the Time Dependent Generator Coordinate Method (TD-GCM) has shown good potential to describe the dynamics of the fission process. This approach yields a time-dependent Schrödinger-like equation that can be solved numerically. Its application to realistic cases has, however, often been limited by its high computational cost. We have recently developed a new solver for the TD-GCM equations based on the finite element method in order to eliminate these limitations. Our code has been extensively tested on several toy-models such as the evolution of a wave packet in a harmonic oscillator potential. Standard refinement methods associated with the finite element approach have been implemented. In our test cases, they improve the numerical accuracy of the method by several orders of magnitudes. Finally, we will show the first results obtained with this new framework for the neutron-induced fission on Pu-239.

Uncertainty Quantification in Nuclear Density Functional Theory for Nuclear Fission

Jordan McDonnell

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Nuclear density functional theory reliably captures the properties of medium-mass and heavy nuclei. It also serves as the backbone to a microscopic theory of nuclear fission, based soundly on the interaction between nucleons. But the predictions of various models have been found to diverge substantially for extreme isotopes and temperatures. Quantifying the theory's inherent uncertainty is essential for making reliable predictions. Through a Bayesian analysis, we calculate the theoretical uncertainty for the parameters of a Skyrme-class energy density functional. We study the propagation of this model uncertainty to the predictions of fission barrier heights.

The Fission Time Projection Chamber

Mike Heffner

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

The goal of the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) is to measure fission cross sections with unprecedented accuracy. The NIFFTE Collaboration has designed and built a Time Projection Chamber (TPC) for this purpose. The 3D tracking capabilities of this device allow for the full reconstruction of charged particles produced by neutron beam induced fissions from a thin central target. The wealth of information gained from this approach will allow cross section systematics to be controlled at the level of 1%. In this talk I will present the current status of the NIFFTE TPC, describe the variety of systematic studies being performed, and outline preliminary results from measurements performed at the Los Alamos Neutron Science Center (LANSCE) facility.

Measurements of high energy neutron standards at NFS, GANIL, France

Cecilia Gustavsson

Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden

In the neutron energy region from 1 to 40 MeV, the most widely used neutron standard cross sections are ^{235}U(n, f) and ^{238}U(n, f). They are often measured relative one another, but there is concern that the ratio is not as well known at these energies as has previously been thought [1]. Below 20 MeV, the primary neutron standard is H(n, n). We suggest an experimental campaign to measure the three cross sections ^{235}U(n, f), ^{238}U(n, f) and H(n, n) simultaneously and relative each other over the whole energy range from 1-40 MeV. To do this, the presently under construction, neutron facility NFS – Neutrons for Science at GANIL, France would be a suitable choice since. NFS will facilitate a high flux of neutrons in the interesting energy range. We plan to use a three-layered target, consisting of the two uranium isotopes on each side of a polyethylene central core. Our detector will detect fission fragments as well as recoil protons from the H(n, n) reaction. Our goal will be to make a high-precision measurement to allow for better known cross section standards, especially in region around and above 20 MeV.

[1] A.D. Carlson, Metrologia 48, S328 (2011).

Neutron-induced cross sections of actinides via the surrogate-reaction method

Quentin Ducasse

CEA Cadarache

The surrogate-reaction method is an indirect way of determining cross sections for reactions that proceed through a compound nucleus (CN). This method was first proposed by J. D. Cramer and H. C. Britt [1] in the seventies to infer neutron-induced cross sections. It consists in using an alternative (or surrogate) reaction to produce the same decaying nucleus as the one formed in the desired neutron-induced reaction. The decay probability induced by the surrogate reaction is measured and the desired neutron-induced reaction is obtained by multiplying the decay probability by the calculated neutron-induced compound-nucleus cross section. The benefit of the surrogate method is that in some cases the target needed is stable or less radioactive than the target of the corresponding neutron-induced reaction. Therefore, the surrogate-reaction method may enable neutron-induced cross sections to be extracted for nuclear reactions on short-lived nuclei that otherwise cannot be measured.

However, one has to consider the spin-parity differences between the neutron-induced and the surrogate reactions. Indeed, at low excitation energies the decay probability may strongly depends on the spin and parity of the compound nucleus. Therefore, we may find differences between the cross sections obtained with the two types of reactions.

We have shown from previous experiments that the surrogate method works well for fission at sufficiently high excitation energy (see e.g. [2]) since the fission cross sections measured with the surrogate method are in good agreement with neutron-induced data. Recently, we have measured for the first time the fission and gamma-decay probabilities of several actinides simultaneously in a surrogate-reaction experiment. In particular, we have investigated the reactions ^{238}U(d,p), ^{238}U(^{3}He,d) , ^{238}U(^{3}He,t) and ^{238}U(^{3}He,^{4}He) as surrogates for the neutron-induced reactions ^{238}U+n, ^{238}Np+n, ^{237}Np+n and ^{236}U+n, respectively. Our first results for the fission cross sections agree fairly well with the neutron-induced data above neutron energies of few hundreds of keV, whereas our capture cross sections are a factor 3 to 10 higher than the neutron-induced data over the whole measured neutron-energy range. This is surprising since according to simple arguments based on the statistical model one would expect that the spin-parity mismatch affects fission and capture cross sections in a similar manner.

In this contribution we will present the experimental procedure, the data analysis and we will discuss the first results of our last experiment.

Fission cross-sections evaluation based on nuclear structure models

Pierre Tamagno

CEA

Over the last decades, improvements in fission theory have resulted in a better understanding of the fission process. However those developments did not yet benefit to the nuclear data evaluation community. The evaluation process amalgamates results from experiments, theoretical and phenomenological models, and systematics in order to supply reliable input data and related covariance matrices for industrial applications. A presentation of current state-of-art in evaluation techniques will be given along with several foreseen improvements under implementation in the CONRAD tool developed at CEA-Cadarache. The CONRAD code was originally designed for cross-section evaluation in resonance energy range. The code has now been extended to deal with most of nuclear data of interest. In energy range above resolved resonances, several methods inspired from the TALYS high-energy cross-section code have been introduced in CONRAD and will be presented. Theses new developments have made relevant the use of more sophisticated models for the treatment of the fission channel above the resonance range. These models rely on nucleus deformation energy profile in order to extract an accurate fission transmission coefficient. The latter is supplied to the Hauser-Feshbach engine to calculate an average cross-section. Two major aspects will be discussed. The numerical methods to be used for an efficient extraction of a fission transmission coefficient from the deformation energy profile (along a single dimension axis) and the calculation of the nuclear energy potential as a function of deformation. Regarding the potential calculation, we use the macro-microscopic model which has been well settled by P. Moller et al. since the 70'. More specifically the 1995 FRDM [1] is being implemented in the CONRAD code and results for isotopes of main interest in reactor physics will be presented.

[1] Moller, P. and Nix, J. R. and Myers, W. D. and Swiatecki, W. J., Atomic Data and Nuclear Data Tables, 1995, **59**, 185

Use of Fission Data in MCNP6

Michael R. James

NEN-5, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

MCNP has used fission data for years in support of its core capabilities. But interest has shifted over the years to more detector modeling and the use of non-Boltzmann tallies. As this has occurred, capabilities have been added, especially with regards to fission multiplicity. Although superior to the original treatment there are still issues with approximations in these models. A quick review of these capabilities will be covered.

In addition, when the CINDER code was implemented into MCNP it became possible to in-line two separate but related capabilities: calculation of delayed particle emissions and isotopic evolution of critical systems (burnup). This was possible in large part because of the nuclear data (esp. fission data) contained in the CINDER package. Although these capabilities in MCNP6 are fairly mature, there are still many approximations have been implemented in these algorithms due to incomplete data. These include Q-value, spectral effects in fission products, time boundary of delayed vs. prompt, etc. This work will discuss how these aspects of fission data are used in MCNP6 and what data needs are foreseen in the future.

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Rapid 3-D Gamma-Ray Response Calculations

Dean J. Mitchell

Sandia National Laboratory

The method that is described in this presentation uses an analytic Detector Response Function (DRF) to combine the outputs from ray-trace and discrete ordinates calculations to compute spectra for three-dimensional descriptions of source objects. The DRF synthesizes the continuum derived from scattered radiation in a way that eliminates the need to explicitly compute interactions with the environment. This method enables computation of gamma-ray spectra in two to three seconds using a one CPU for single object models such as cylinders and plates. Calculations are completed in less than one minute for configurations that comprise a dozen discrete objects. Evaluations for a limited set of benchmark measurements have demonstrated that computed spectra are as accurate as can be achieved by computational methods that require orders of magnitude more computational time. Additional testing is required to validate the calculations for complex source configurations, and deficiencies that are identified by these tests will be addressed.

Correlations in Prompt Neutron and Gamma Ray Emissions from Fission

Sara Pozzi

Department of Nuclear Engineering & Radiological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA

I will present new experiments and simulations of correlated, prompt neutron and gamma rays emissions from fission. Experiments to measure these correlations were performed using organic scintillators, including prompt neutron-neutron and neutron-gamma ray correlations. The experimental arrangements allow for the measurement of the angular distributions of emissions, as well as some energy spectroscopy.

The results from these experiments are used to improve the physics models in our Monte Carlo codes. In addition, the results are compared to results from the theory of neutron and gamma ray emission in event-by-event modeling of the fission process. These observables are of interest in the development of new systems for the detection and characterization of special nuclear materials.

Delayed Neutron and Gamma Measurements of Special Nuclear Materials at the Royal Military College of Canada

M.T. Andrews[1,2], E.C. Corcoran[1], D.G. Kelly[1], J.T. Goorley[2]

[1] Royal Military College of Canada, P.O. Box 17000 Stn Forces, Kingston, ON, K7K 7B4, Canada
[2] Monte Carlo Codes & Radiation Transport Applications, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Measurements of delayed neutron (DN) and delayed gamma (DG) emissions from fission products are used at the Royal Military College of Canada (RMCC) to identify and characterize special nuclear materials (SNM). A delayed neutron and gamma counting (DGNC) system sends microgram quantities of SNM to the facilitys SLOWPOKE-2 research reactor where they are exposed to a predominately thermal neutron flux. Upon the elapse of irradiation, samples are sent to an array of ^{3}He detectors and a high purity germanium detector (HPGe), which record neutron and gamma emissions as a function of count time. This talk will describe the DNGC system and the measurements of ^{233}U, ^{235}U, and ^{239}Pu. The identification and characterization of SNM mixtures via an analysis of temporal DN and DG emissions will also be discussed. Finally, comparisons of RMCC measurements to MCNP6 simulations of DN and DG emissions will be included.

High Precision Measurement of ^{236}U(n,γ) Cross-Section

B. Baramsai[1], M. Jandel[1], T. A. Bredeweg[1], G. Rusev[1], C. Walker[1], A. Couture[2], S. Mosby[2], J. L. Ullmann[2]

[1] C-NR, Los Alamos National Laboratory, Los Alamos, NM 87545

[2] LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545

We present preliminary results of the ^{236}U(n,γ) reaction cross-section measurements carried out using the Detector for Advanced Neutron Capture Experiments (DANCE) at the Los Alamos Neutron Science Center (LANSCE). In the experiment we have used several different targets with different thicknesses and isotopic compositions of ^{236}U and ^{235}U, so that the ratio method described in [1] could be implemented.

A primary goal of the measurement is to obtain high precision capture cross-section data on ^{236}U with improved uncertainties (less than 3%), for the incident neutron energy range from 1 keV up to about 1 MeV. The high precision cross-section data are of great interest to both Defense and Nuclear Energy Programs and are considered a high priority for the stockpile stewardship and advance fuel cycle programs.

The conference poster will include some details about the accurate off-line data analysis techniques such as background subtractions, consideration of the experimental conditions that affect the precision of cross-section determination [1, 2, 3].

This research is supported by the U.S. Department of Energy, Office of Science, Nuclear Physics under the Early Career Award No. LANL20135009.

[1] M. Jandel *et al.*, Phys. Rev. Lett **109**, 202506 (2012).

[2] M. Jandel *et al.*, Phys. Rev. C **78**, 034609 (2008).

[3] S. Mosby *et al.*, Phys. Rev. C **89**, 034610 (2014).

Measuring ^{244}Cm α/Spontaneous Fission Branching Ratio with the NIFFTE fissionTPC

Jeremy Bundgaard

Physics Department, Colorado School of Mines, USA

The NIFFTE collaboration has designed the fission Time Projection Chamber (fissionTPC) to measure the energy dependent neutron induced fission cross sections of heavy actinides to less than 1% error. The fissionTPC has the unique capability to discriminate fission fragments from other decay particles using 3D track imaging. Sub percent error is needed to progress toward future designs of Gen IV reactors. The rich data from track ionization profiles enable dE/dx and Bragg Peaks to be studied for unprecedented particle identification. Track information enables access to parameter spaces from which we can better understand straggling effects that systematically limit the accuracy of typical cross section measurements done by fission chambers.

Energy Dependence of Fission Product Yields from ^{235}U, ^{238}U and ^{239}Pu for Mono-energetic Neutrons Between 0.5 and 14.8 MeV

Matthew Gooden

North Carolina State University

A joint collaboration between the Triangle Universities Nuclear Laboratory (TUNL) and LANL-LLNL has made a set of absolute cumulative fission product yield measurements. With mono-energetic neutrons produced at the TUNL 10 MV Tandem Accelerator, at five incident energies between 0.5 and 14.8 MeV, the cumulative fission product yields from ^{235}U, ^{238}U and ^{239}Pu have been measured for a number of fission products. These measurements combine the use of a dual-fission ionization chamber and γ-ray spectroscopy. The specially constructed dual-fission chamber allows an accurate determination of the absolute rate of fission in the activation target by simple mass scaling. The γ-ray spectroscopy is performed with shielded High-Purity Germanium (HPGe) detectors at the TUNL low-background counting area. These fission product yield measurements have practical application to the US weapons program, as well as fuel burn-up in advanced reactors. The fission product mass distribution is one of the most striking features of fission and its dependence on incident neutron energy provides valuable insight into the fission process.

Measurement of neutron multiplicity as a function of fission fragment mass and excitation energy for ^{239}Pu(n,f) E_n=1-20 MeV

Jonathan King

Division of Nuclear Chemistry, Oregon State University

The neutron multiplicity [ν] of the fission reaction is well documented for thermalized neutrons. We propose to measure neutron multiplicity as a function of excitation energy and fragment mass [$\nu(A, E)$] for E_n=1-20 MeV which has potential implications in both weapon and fast reactor designs. A first attempt at this experiment was done at LANSCE-WNR in the Fall of 2013. Though useful TKE data was published out of the effort, we were ultimately unable to extract ν(A,E) due to inadequate beam rates, solid angle coverage, and electronics. We have proposed a second attempt at this experiment to run at WNR in the upcoming beam cycle. This attempt should be successful due to dramatically improved solid angle and increased beam intensity.

Fragment Angular Distributions in Neutron-Induced Fission of ^{235}U and ^{239}Pu using a Time Projection Chamber

Verena Kleinrath

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Fission fragment angular distributions can lend insights into fission barrier shapes and level densities at the scission point, both important for fission theory development. Fragment emission anisotropies are also valuable for precision cross section ratio measurements, if the distributions are different for the two isotopes used in the ratio. Available angular data is sparse for ^{235}U and even more so for ^{239}Pu, especially at neutron energies above 5 MeV. The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) time projection chamber, which enables precise tracking of charged particles, can be used to study angular distributions and emission anisotropies of fission fragments in neutron-induced fission. In-beam data collected at the Los Alamos Neutron Science Center with a $^{239}Pu/^{235}U$ target in the upcoming 2014 runcycle will provide angular distributions as a function of incident neutron energy for these isotopes.

Research activities using Tandem and HIGS facilities at TUNL

Fnu Krishichayan

TUNL/Duke University

Current ongoing research activities using Tandem and High Intensity Gamma-ray Source (HIGS) at TUNL will be presented, e.g., Precise neutron-induced cross-section measurements, NRF measurements on spherical and deformed nuclei, feasibility test of the photon-induced FPY measurements.

Digital Shaping Algorithms for GODDESS

S.J. Lonsdale[1], J.A. Cizewski[1], A. Ratkiewicz[1], and S.D. Pain[2]

[1] Rutgers University
[2] Oak Ridge National Laboratory

Gammasphere-ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) combines the highly segmented position-sensitive silicon strip detectors of ORRUBA with up to 110 Compton suppressed HPGe detectors from Gammasphere, for high resolution for particle-gamma coincidence measurements. The signals from the silicon strip detectors have position-dependent rise times, and require different forms of pulse shaping for optimal position and energy resolutions. Traditionally, a compromise was achieved with a single shaping of the signals performed by conventional analog electronics. However, there are benefits to using digital acquisition of the detector signals, including the ability to apply multiple custom shaping algorithms to the same signal, each optimized for position and energy, in addition to providing a flexible triggering system, and a reduction in rate limitation due to pile-up. Recent developments toward creating digital signal processing algorithms for GODDESS will be discussed.

This work is supported in part by the U.S. D.O.E. and N.S.F.

Plutonium Metal Spontaneous Fission Neutron Cross-Correlation Measurements

Matthew J. Marcath[1], Tony Shin[1], Shaun D. Clarke[1], Jennifer L. Dolan[1], Marek Flaska[1], Edward W. Larsen[1], Sara A. Pozzi[1] and Paolo Peerani[2]

[1] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Michigan, USA

[2] European Commission, Joint Research Centre, Ispra, Italy

A plutonium metal sample was measured by a fast-neutron multiplicity counter for characterization of spontaneous fission neutron anisotropy and for verification of MCNPX-PoliMi calculations. Accurate neutron angular distribution models are important to properly simulating fast neutron coincidence measurements for nuclear nonproliferation and safeguards. A majority of prompt neutrons are emitted from fully accelerated fission fragments; those neutrons carry momentum from the fission fragments, and thus an anisotropic neutron angular distribution is observed in the laboratory reference frame. The fast-neutron multiplicity counter was used with pulse shape discrimination techniques to produce neutron-neutron cross-correlation time distributions from spontaneous fission in a lead-shielded 0.84 g $^{240}Pu_{eff}$ metal sample. Due to neutron anisotropy, the number of observed neutron cross-correlations varied as a function of angle between a detector pair and fission source. Fewer neutron correlations were observed at detector angles near 90 degrees, relative to higher and lower detector angles. Both the neutron correlations as a function of time difference and detector pair angle are compared with MCNPX-PoliMi calculations and show good agreement.

Keywords: Monte Carlo, safeguards, measurement, plutonium

Development of fission-fragment detectors

G. Rusev, M. Jandel, E. Bond, J. Daum, A. Roman, R. Springs

Los Alamos National Laboratory

Investigation of prompt fission gamma rays and neutron-capture gamma rays from a fissile actinide target at the Detector for Advanced Neutron Capture Experiments (DANCE) requires usage of a fission-fragment detector to provide a trigger or a veto signal, respectively. Development of two types of fission-fragment detectors, Parallel Plate Avalanche Counter (PPAC) and Thin scintillator Film Detector (TFD), will be presented. Multiple target PPAC and TFD detectors are being considered for future DANCE experiments in order to improve our understanding of isomeric states populated after neutron capture and neutron-induced fission of U-235.

Work on the detector development was supported by the U.S. Department of Energy, Office of Science, Nuclear Physics under the Early Career Award No. LANL20135009.

Development of the New SPIDER Detector at LANSCE

Dan W. Shields

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Fission product yields (FPY) are crucial to a better understanding of the fission process. These data impact our modeling of next generation nuclear power and our confidence in the current stockpile. A small and partially conflicting set of FPY experimental results at higher than thermal neutron energies for critical actinides in ENDF and other nuclear libraries produces a need for new precision measurements.

The SPIDER (SPectrometer for Ion DEtermination in fission Research) detector is being developed at LANSCE-WNR (Los Alamos Neutron Science CEnter - Weapons Neutron Research) to fill this need. The detector will have exceptionally high fragment mass and incident neutron energy resolution allowing for unprecedented measurements of the FPY directly after fission takes place.

An overview of the detector components, data acquisition system, simulations, and preliminary test results will be presented.

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Improving SCALE from Nuclear Physics

Kemper Talley

Nuclear Energy, Energy Science and Engineering, University of Tennessee, Knoxville, TN 37996, USA

One of the goals of nuclear theory is to improve nuclear engineering calculations, specifically in the area of beta decay. The Hartree-Fock-Bogoliubov equations over a Pschl-Teller-Ginocchio basis (HFB/PTG) allow us to effectively probe beta decay that leads to delayed neutron emission in the region of weakly bound nuclei. Updates to delayed neutron data are needed from both experiment and theory in order to provide effective calculations for the decay heat problem and other applications.

Neutron Capture Rate Measurements Using a Lead Slowing-Down Spectrometer

Nicholas Thompson

Rensselaer Polytechnic Institute

This work aims to measure neutron capture rates using a Lead Slowing-Down Spectrometer (LSDS) coupled with a pulsed neutron source. Simulations using the Monte Carlo N-Particle Transport (MCNP) suite of codes were performed to design the detectors and experiments. Experiments were performed at the Rensselaer Polytechnic Institute (RPI) Gaerttner Linear Accelerator Center (LINAC) measuring the capture rate tantalum and molybdenum. The high gamma background in the LSDS is a limiting factor and experiments and simulations with different types of detector were performed in order to maximize the signal to background ratio.

Potential to Advance the Thorium Fuel Cycle with the NIFFTE fissionTPC

Rusty Towell

Department of Engineering and Physics, Abilene Christian University, Abilene, TX 79699, USA

The NIFFTE fission Time Projection Chamber (fissionTPC) is a powerful tool that is being developed to take precision measurements of neutron-induced fission cross sections of transuranic elements. During the last run at the Los Alamos Neutron Science Center (LANSCE) the fully instrumented TPC took data for the first time. The exquisite tracking capabilities of this device allow the full reconstruction of charged particles produced by neutron beam induced fissions from a thin central target. The wealth of information gained from this approach will allow cross section systematics to be controlled at the level of 1%. These results are critical to the development of advanced uranium-fueled reactors. However, there are clear advantages to developing thorium-fueled reactors including the abundance of thorium verses uranium, minimizing radioactive waste, improved reactor safety, and enhanced proliferation resistance. The advantages of a thorium fuel cycle will be discussed along with the potential for using the fissionTPC to measure needed cross sections.

Measurements of fission fragments in coincidence with prompt fission gamma rays at DANCE

Carrie Walker

Nuclear and Radiochemistry Group, C-NR, Los Alamos National Laboratory

Modern models of fission are capable of calculating not just average quantities but also distributions of all fission products. These models employ a Monte Carlo implementation of statistical nuclear reaction theories, such as Hauser-Feshbach, to describe the de-excitation of fission fragments, but they require more parameters to completely describe the system. Neutrons carry away most of the excitation energy of fission fragments, though gamma rays would contribute in the last stage of de-excitation. Because neutrons carry off only a small fraction of initial angular momentum of fission fragments, gamma-ray multiplicity distributions can give information about the initial distribution of angular momentum of the pre-emission fragments. Detailed experimental information on correlations between fission fragment properties and prompt neutron and gamma rays can thus help constrain fission models by providing information about pre-emission fragments, which are otherwise difficult to measure.

Our goal is to measure fission fragment kinetic energy in coincidence with gamma rays. The measurement will be carried out with the Detector for Advanced Neutron Capture Experiments (DANCE), the 4π gamma-ray calorimeter located at flight path 14 of the Lujan Center. Two fission fragment detectors will be installed in the center of the DANCE array, and measurements of fission fragments and gamma rays will be performed simultaneously. Benchmark measurements will be performed with a Cf-252 spontaneous fission source, followed by a measurement of neutron-induced fission of U-235. A prototype fission fragment detector has been constructed and is ready for testing. We have also modeled the design geometry of the fragment detectors using GEANT4 and simulated their response to fission events generated from theory using the CGMF code. Results of simulations are presented. Once this experiment is incorporated with the proposed NEUANCE neutron detector array at DANCE, data on neutrons, gamma rays and fission fragments will all be collected simultaneously.

[LA-UR-14-26957]

Nuclear fission research at Los Alamos

Mark B. Chadwick

Los Alamos National Laboratory, Los Alamos, NM, USA

I will give a brief overview of the nuclear fission research program at Los Alamos, and provide some perspectives on why it is important.

The following areas will be addressed:

a) The prompt fission neutron spectrum. This is being measured by the Chi-nu experiment. I will explain the challenges we face to advance our understanding here.

b) The fission cross section. The time projection chamber (TPC) experiment has a goal of determining key actinide cross sections to unprecedented accuracy.

c) Fission product yields. Both the SPIDER experiment and experiments at Triangle University Nuclear Laboratory (TUNL) are seeking to more accurately determine the energy-dependence of fission product yields.

d) Prompt fission gamma spectra. These data, from DANCE, have a number of applications including the new Neutron-Diagnosed Subcritical Experiment (NDSE), which will be briefly discussed.

Experimental Fission Research at the Gaerttner LINAC Center at Rensselaer Polytechnic Institute

Yaron Danon, E. Blain

Gaerttner LINAC Center, Rensselaer Polytechnic Institute, Troy, NY 12180

The Gaerttner LINAC center at RPI is housing a 60 MeV electron accelerator which is used for variety of applications. Recently two experimental methods were developed to study some properties of the fission process.

In the first experiment the RPI Lead Slowing-Down Spectrometer (LSDS) was used to measure the neutron energy dependent fission fragment mass and energy distributions. Experiments were done with ^{252}Cf, ^{235}U and ^{239}Pu samples in the incident energy rage from 0.1 eV to 1.4 keV. In this research a double gridded fission chamber is used in the LSDS, which provides a large neutron flux, and thus enables measurements with microgram samples of fissile while overcoming background from sample decay. This method also enables simultaneous measurement of the fission cross section in the energy range from 0.1 eV to several keV.

In the second experiment the objective is to study the possibility of measuring the prompt fission neutron spectrum using a gamma multiplicity tag. The method was first demonstrated with ^{252}Cf followed by an incident neutron beam experiment with ^{238}U. This method enables the use of a relatively larger mass sample without the need to construct a multiplate fission chamber, advantages and disadvantages will be discussed.

Prompt Fission Neutron Spectrum Measurements using a Gamma Tagging Method

Ezekiel Blain, Y.Danon

Gaerttner LINAC Center, Rensselaer Polytechnic Institute, Troy, NY 12180

Measurements of the prompt fission neutron spectrum have been performed at RPI using a multiple gamma tagging method. This method utilizes the high gamma multiplicity from fission to tag when a fission event has occurred, as opposed to the measurement of fission fragments in conventional fission chambers. This allows for much larger samples to be measured since the penetrability of gamma rays is much greater than that of fission fragments. By taking gamma coincidence on an array of BaF_2 detectors, the fission event can be isolated from other events such as capture and scattering. The measurement uses EJ301 liquid scintillators to measure the high energy portion of the spectrum, 500 keV to 7 MeV, and a thin plastic scintillator to measure the low energy portion of the spectrum, 50 keV to 2 MeV. The prompt fission neutron spectrum has been measured for the spontaneous fission of ^{252}Cf for the energy range from 50 keV to 7 MeV and shows good agreement with current evaluations. Preliminary work on neutron induced fission of ^{238}U has also been performed and highlights the advantage of the gamma tagging method to utilize much larger samples than can be measured with conventional fission chambers and eliminates the need for complex multiplate fission chambers.

Current and future fission research at DANCE

Marian Jandel

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Measurements of correlated data on prompt-fission gamma-rays have been carried out for various isotopes in recent years using Detector for Advanced Neutron Capture Experiments (DANCE). The studies of the fission reaction were needed in order to improve cross section data for neutron capture on isotopes such as U-235 and Pu-239. These measurements were performed with the help of fission fragment tagging detectors and resulted in new correlated data for prompt-fission gamma-rays.

To enhance our understanding of gamma-ray emission after fission and capture, new detection capabilities are under development at DANCE. A new compact segmented array NEUANCE (NEUtron detector Array at daNCE) will provide new capability for measurements of correlated data on fission neutrons and gammas. NEAUNCE will consist of liquid scintillators capable of discriminating neutrons and gamma rays from the pulse shape. It will be installed in the central cavity of the DANCE array, around the beam line. The low energy neutrons from the beam won't deposit enough energy in liquid scintillators and therefore the fission neutrons will be readily identified. This approach will also enable the use of thick targets to obtain large counting statistics.

An upgrade of the DANCE data acquisition system is also in progress. Up to two hundred channels of fast 500 MHz 14-bit digitizers were purchased with the FPGA on-board signal processing. The new system will provide improved resolution, larger data throughput and flexibility for future integration of auxiliary detectors, such as NEUANCE.

Finally, the development of fission fragment detectors is under way to measure total kinetic energy and masses of fission fragments. Coupling all these developments together in future, would allow simultaneous measurements of fission neutrons, gammas and fragments.

LA-UR-14-26380

Development of a New Tool called FALSTAFF to Study the Fission Process

Cédric Golabek[1], D. Doré[1], F. Farget[2], F.-R. Lecolley[3], G. Lehaut[3], T. Materna[1], J. Pancin[2], S. Panebianco[1], T. Papaevangelou[1]

[1] CEA, Centre de Saclay Irfu/Service de Physique Nucléaire, 91191 Gif-sur-Yvette, France

[2] GANIL, CEA/DSM-CNRS/IN2P3, bd H. Becquerel, F-14076 Caen, France

[3] LPC Caen, ENSICAEN, Université de Caen, CNRS-IN2P3, F-14050 Caen Cedex, France

Nuclear fission is a process whose understanding is still undergoing. The development of microscopic and phenomenological models, aiming at a detailed description of the final state observables, needs precise and coherent nuclear data on fission fragment characteristics. The quality of these nuclear data and models has a strong impact on several applications. The main one is the knowledge of production yields of neutron poisons and neutron multiplicity of nuclei fissioning in the nuclear core for the control of nuclear reactors. This is also important for high energy fission concerning the development of fast reactors.

In this framework, a new experimental setup called FALSTAFF (Four Arm cLover for the Study of Actinide Fission Fragments) is under development. It will allow a complete characterization (i.e. mass, nuclear charge and kinetic energy) of both fission fragments. Moreover the simultaneous measurement of the velocity (determined from the TOF measurement provided by two SED detectors) and kinetic energy (ensured by an ionization chamber) of both fission fragments will give access to their mass before and after neutron evaporation. Therefore, the neutron multiplicity can be extracted from their mass difference. FALSTAFF will be dedicated mostly to study neutron induced reactions on actinide targets. It will therefore be able to take advantage of the NFS (Neutron For Science) facility, being built presently at GANIL, which will produce high intensity neutron beams from hundreds of keV up to 40 MeV.

A fully equipped arm, composed of two TOF detectors and an ionization chamber, is presently being tested at CEA Saclay with a spontaneous fission source. Time and spatial resolutions have been measured and included in a realistic Geant4 simulation allowing to assess the expected resolutions of physics variables. The measurement of velocity, positions and energy in coincidence has been achieved leading to the mass distribution of fission fragments after neutron evaporation. Comparison of experimental data and simulation will be shown and discussed. The outlook of the project in the near future and further will be presented.

Fission activities at the ILL Lohengrin spectrometer: review and perspectives

Christophe Sage

Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France

The studies of different innovative fuel cycle aspects such as the calculation of residual heat or poison concentration in the fuel, requires the detailed knowledge of isotopic and mass fission yields. Presently, fission models are not able to predict the yields with an acceptable accuracy. An experimental program has therefore been initiated - within the frame of a collaboration between the ILL and laboratories from CEA and CNRS - to get a thorough characterization of fission yields in mass, charge, kinetic energy and spin distributions.

The talk will begin with a brief review of the current measurements of the isotopic and mass fission yields for the ^{233}U(n_{th}, f), ^{241}Pu(n_{th}, f) and ^{241}Am(n_{th}, f) reactions performed at the Lohengrin recoil mass spectrometer of the ILL. Mass yields are obtained with an ionisation chamber placed at the exit of the separator, whereas the isotopic yields are determined by delayed gamma spectrometry using two high purity Ge clover detectors placed subsequent to the spectrometer.

The second part of the talk will be dedicated to the evaluation of the fragment spin distribution via the measurement of their isomeric ratios. We will present different experimental methods using the Lohengrin spectrometer (coincidence, beam cut and distribution deconvolution) adapted to isomers with half-lives ranging from a few nanoseconds to a few minutes. One of the purposes is to compare the measured isomeric ratios with the results of simulations of the neutron and gamma ray cascades following fission, such as those performed by the Fifrelin code developed at CEA Cadarache.

Finally a future instrument of the ILL partly dedicated to the fission process study (called FIPPS for FIssion Product Prompt gamma ray Spectrometer) will be presented. It will be based on the combination of an array of high efficiency gamma ray detectors and a gas filled magnet. Its main features will be detailed, such as the possibility of studying both prompt gamma rays and neutron evaporation. Results from test measurements achieved by converting the last constitutive magnet of the Lohengrin spectrometer into a gas filled magnet will be exposed. Several gases and pressures were tested and compared to a dedicated simulation code developed at the LPSC, the aim of which is to assess the design and dimensions of the FIPPS gas filled magnet.

A Neutron Source for Fission Yield studies at IGISOL-JYFLTRAP

Andrea Mattera

Division of Applied Nuclear Physics, Uppsala University, Uppsala, Sweden

The IGISOL-JYFLTRAP facility at Jyváskylá University (Finland) has recently been upgraded and equipped with a new MCC-30/15 high intensity cyclotron that is designed to deliver up to 200 μA of protons (deuterons) at 30 MeV (15 MeV). This opens the way to the use of the IGISOL-JYFLTRAP online mass separator and Penning trap for studies of neutron-induced fission yields.

For this purpose, a proton-neutron converter consisting of a 5-mm-thick water-cooled beryllium target has been designed. The neutron energy spectrum has been simulated with two different codes (FLUKA and MCNPX) and a measurement has been performed at The Svedberg Laboratory (Uppsala, Sweden) in June 2012.

The idea behind the design is to have a simple geometry that can be changed according to needs (using thinner beryllium targets to harden the spectrum or adding a moderator to thermalize it). This will allow to study the energy dependence of fission yields.

A prototype of the proton-neutron converter has been installed in its planned position at IGISOL-JYFLTRAP and the neutron flux has been measured in the position of the fission target in March 2014. Thin Film Breakdown Counters and a simple TOF setup have been used to estimate the flux of neutrons, to be compared with information from neutron activation samples positioned in a similar geometry.

The validation of Monte Carlo calculations with this experiment in the final configuration will allow the use of the proton-neutron converter for FY studies.

The planned measurement campaign of n-induced fission yields is aimed both at improving measurements of already studied actinides, and at measuring actinides and energy ranges for which data is scarce or non-existent. To validate and optimize the experimental setup the first measurement will be performed with ^{238}U using the 5-mm beryllium target. Thereafter it will be possible to vary a number of parameters such as the energy spectrum and fissile material.

The University of New Mexico Fission Fragment Spectrometer

Adam Hecht

University of New Mexico

Fission cross section and fragment yields are important for active interrogation, for understanding secondary reactor heating, and for furthering theory on fission preformation. Very little data exists on fragment distributions though. We are in a multi-year project with the LANL SPIDER collaboration, with the University of New Mexico (UNM) prototyping its own fission fragment spectrometer and detector components and performing independent measurements with neutron beams at LANSCE. The UNM Fission Fragment Spectrometer consists of a heavy ion time-of-flight (TOF) module followed by an ionization chamber (IC), for velocity and KE measurements, respectively, of the ejected fission fragments. These particle-by-particle measurements, combined, give the masses of the fission fragments, A. Initial fission data will be presented for n + U-235 work performed at LANSCE and runs at UNM using Cf-252. Future iterations of the spectrometer are planned to move towards high resolution with 1 amu mass resolution for heavy fragments. We are also working on active cathode timing to understand fragment penetration into the IC gas for proton number, Z, determination, which will be discussed. Thus, with dual arms to examine both fragments from binary fission, we will record A, Z, and KE of both fragments on an event-by-event basis, and thus also neutron multiplicity and cross sections for each fragment pair.

Characteristics of prompt fission gamma-ray emission & advances in measurements, evaluations and predictions

Andreas Oberstedt

Chalmers University of Technology

In recent years the measurement of prompt-fission gamma-ray spectra (PFGS) has gained renewed interest. After about forty years since the first (and at the same time last) comprehensive studies on this topic, the development of lanthanide halide scintillation detectors as well as new data acquisition and signal-processing techniques provided appropriate tools to determine PFGS characteristics with unprecedented accuracy. These new experimental efforts were motivated by OECD/NEA requests for new values especially for gamma-ray multiplicities and mean photon energies, in particular for 235U and 239Pu. Both isotopes are considered the most important ones with respect to the modelling of innovative cores for fast Generation-IV reactors.

We present recent experimental results from the reactions $^{235}\mathrm{U}(n_{\mathrm{th}}, f)$ and $^{241}\mathrm{Pu}(n_{\mathrm{th}}, f)$ as well as from the spontaneous fission of $^{252}\mathrm{Cf}$, together with corresponding calculated values, when available. We compare our results with systematics for PFGS characteristics as function of both atomic and mass number of the compound systems, established by T.E. Valentine [1]. Although the parameters in that work might need a revision due to the results from recently performed measurements, this systematics may allow estimating gamma-ray multiplicity, mean and total photon energy in cases, where target nuclei are not available or accessible experimentally. While this has been done for thermal neutron induced and spontaneous fission, we show how PFGS characteristics may be predicted for fission induced by fast neutrons.

[1] T.E. Valentine, Ann. Nucl. Energy 28 (2001) 191.

Event-by-Event Fission Modeling

Ramona Vogt[1,2]

[1] Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94551, USA
[2] Physics Department, University of California, Davis, California 95616, USA

For many years, the state of the art for treating fission in radiation transport codes has involved sampling from average distributions. However, such "average" fission models have limited interaction-by-interaction capabilities. Energy is not explicitly conserved and no correlations are available because all particles are emitted isotropically and independently.

However, in a true fission event, the energies, momenta and multiplicities of emitted particles are correlated. Such correlations are interesting for many modern applications, including detecting small amounts of material and detector development. Recently, several Monte Carlo codes have become available that calculate complete fission events. Event-by-event techniques are particularly useful because it is possible to obtain the fission products as well as the prompt neutrons and photons emitted during the fission process, all with complete kinematic information. It is therefore possible to extract any desired correlation observables. Such codes, when included in broader Monte Carlo transport codes, such as `MCNP`, can be made broadly available to the community.

The fast event-by-event fission code `FREYA` (Fission Reaction Event Yield Algorithm), one such code, generates large samples of complete fission events. We compare our `FREYA` results with available data on prompt neutron and photon emission. In particular, we compare with neutron-neutron correlation data. `FREYA` has been integrated into the LLNL fission library which is part of `MCNP6`. We also discuss the integration that has taken place so far.

Prompt gamma-ray production in neutron-induced fission of ^{239}Pu

J.L. Ullmann[1], S.M. Mosby[1], M. Jandel[1], C.Y. Wu[2], J.A. Becker[2], E.M. Bond[1], T.A. Bredeweg[1], A. Chyzh[2], A. Couture[1], J. Gostic[2], R.C. Haight[1], A.C. Hayes[1], R. Henderson[2], T. Kawano[1], H.Y. Lee[1], E. Kwan[2], J.M. ODonnell[1], I. Stetcu[1], T.N. Taddeucci[1], P. Talou[1], D.J. Vieira[1], J.B. Wilhelmy[1]

[1] Los Alamos National Laboratory, Los Alamos, NM, USA 87545

[2] Lawrence Livermore National Laboratory, Livermore, CA, USA 94550

Detailed knowledge of the properties of gamma rays emitted from fission is important not only for understanding the basic fission process and energy balance, but also for applications such as nuclear energy and global security. A comparison of measurements to theoretical calculations tests our ability to model gamma-ray emission. A measurement of the total gamma energy, individual gamma energy, and multiplicity spectra for neutron-induced fission of ^{239}Pu [1] was recently made using the nearly 4π DANCE detector at the Los Alamos Neutron Science Center (LANSCE). The measurement was made over the neutron energy range from 10 eV to roughly 30 keV, but the published spectra were limited to results from the 10.93 + 11.89 eV 1^+ resonance complex. Fission events were tagged using a small PPAC, containing roughly 1 milligram of highly enriched (99.967%) ^{239}Pu. The PPAC was inserted into the center of the DANCE array. Even with a highly efficient detector array, corrections for detector response are important, and two methods for making the correction are described. The resulting spectra will be compared to other data, global parameterizations, and recent model calculations. The average total gamma-ray energy was estimated to be 7.46 ± 0.06 MeV/fission, about 10% higher than the ENDV/B-VII.1 evaluation.

[1] J.L. Ullmann, Phys. Rev. C **87**, 044607 (2013).

Prompt fission neutron and gamma-ray properties in a Monte-Carlo Hauser-Feshbach framework

Ionel Stetcu

Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

The fragments produced during the fission process are good examples of compound nuclei, whose de-excitations, primarily via emission of neutrons and gamma rays, can be described in the Hauser-Feshbach framework. In this talk, I will present our Monte-Carlo implementation of the Hauser-Feshbach statistical model to the de-excitation of the hot fission fragments via neutron and gamma emission. This flexible approach allows us to describe not only average quantities, like in the Los Alamos model, but also distributions and correlations between the emitted particles. Simulated prompt fission gamma-ray properties will be compared to recent experimental results on prompt fission gamma-ray energy and multiplicity distributions obtained at the DANCE facility at LANSCE, as well as the research reactor KFKI in Budapest, Hungary. In this context, I will discuss the impact of various assumptions, e.g., initial angular momentum distributions of the fission fragments, on selected observables, and, consequently, on the predictive capability of our computational method.

Beta-delayed neutron studies of fission fragments

Robert Grzywacz

Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

Beta-delayed neutron emission (βn) is a dominant decay channel for the majority of very neutron-rich nuclei. This decay mode can be due to the Gamow-Teller type transitions to the highly excited states in beta decay daughter nucleus. Energy-resolved measurements of neutrons probes directly the strength distribution, which is an essential component of the decay lifetime models. A new detector system called the Versatile Array of Neutron Detectors at Low Energy (VANDLE) [1,2] was constructed in order to study decays of very neutron-rich fission fragments produced at present-day facilities. The first experimental campaign at the Holifield Radioactive Ion Beam Facility investigated neutron energy spectra of fission fragments, in key regions of the nuclear chart: near the shell closures at ^{78}Ni and ^{132}Sn, and for the deformed nuclei near ^{100}Rb. In several cases, high-energy neutron structures were observed, which were interpreted to be due to large amplitude Gamow-Teller transformations.

[1] C. Matei et al., Proceedings of Science, NIC X, 138 (2008).

[2] S. Paulauskas et al., NIM A 737, 22 (2014).

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Prompt Fission Neutron Studies at LANSCE

Hye Young Lee[1], R.C. Haight[1], T.N. Taddeucci[1], T.A. Bredeweg[1], B. Bucher[2], M. Devlin[1], N. Fotiades[1], R.A. Henderson[2], S. Mosby[1], R.O. Nelson[1], D. Neudecker[1], J.M. O'Donnell[1], S.A. Wender[1], and M.C. White[1] and C.Y. Wu[2]

[1] Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM, 87545

[2] Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA, 94551

Prompt-fission-neutron (PFN) spectra for neutron-induced fission reactions on uranium and plutonium isotopes are important for nuclear applications. Currently available sets of PFN data on ^{239}Pu show an experimental uncertainty as large as 30 % and discrepancy in spectral shape. As an effort to improve the quality of data, the Chi-Nu project, jointly conducted by LANL and LLNL, is designed to use 22 ^{6}Li-glass scintillation detectors for measuring low energy PFNs (<1 MeV) and 56 liquid scintilators for higher energy PFNs for the incoming neutron energy of 0.5-20 MeV at the Los Alamos Neutron Science Center (LANSCE).

To better understand the response of ^{6}Li-glass detectors in the energy range from 50 keV to 1 MeV, which is one of the major systematic uncertainties, measurements of well-known spontaneous-fission neutrons from the ^{252}Cf Parallel-Plate Avalanche Counter (PPAC) were done in the same neutron-beam flight path. Results were compared with Monte Carlo simulations (MCNP-PoliMi) and they show good agreement. Similar measurements with a ^{7}Li-glass detector were used to assess gamma-ray background yields, and ^{6}Li-glass experimental yields on ^{235}U were used to investigate neutron-beam induced backgronds. Preliminary reports on reduced backgrounds and systematic uncertainties will be discussed.

Measurement of the prompt fission neutron energy spectrum for ^{238}U(n,f) at 1.2, 2, 5.2 and 15 MeV and for ^{235}U(n,f) at 500 keV - Preliminary results

Alix Sardet[1], C. Varignon[1], B. Laurent[1], T. Granier[1], A. Oberstedt[1,2], F.-J. Hambsch[3], C. Matei[3]

[1] CEA, DAM, Île-de-France, F-91297 Arpajon, France

[2] Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden

[3] European Commission, Joint Research Centre (IRMM), B-2440 Geel, Belgium

Prompt fission neutron energy spectra occupy a key position for reliable predictions of the behaviour of nuclear systems, but also for an accurate modelling of the fission process itself. As models and evaluations are adjusted to experimental data, the International Atomic Energy Agency (IAEA) highlighted the need for a more complete and exact database [1]. In this sense, measurements on ^{238}U(n,f) were performed at the 4 MV Van de Graaff accelerator facility of the CEA/DAM in Bruyères-le-Châtel and on ^{235}U(n,f) on the 7 MV Van de Graaff accelerator of the Joint Research Center (IRMM) in Geel. We present results from the characterization of the detectors in use (fission chamber, p-terphenyl and BC501A scintillators) and show first results from measurements of the reactions ^{238}U(n,f) and ^{235}U(n,f), induced by neutrons of 1.2, 2, 5.2 and 15 MeV as well as 500 keV incident energy, respectively.

[1] R. Capote et al. (January 2009), "Consultants Meeting on Prompt Fission Neutron Spectra of Major Actinides, Summary Report," IAEA-INDC International Nuclear Data Committee, INDC(NDS)-0541.

Open questions concerning the evaluation of the ^{239}Pu prompt fission neutron spectra up to 30 MeV incident neutron energy

Denise Neudecker, P. Talou, T. Kawano

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, USA

Evaluated prompt fission neutron spectra (PFNS) of ^{239}Pu from thermal up to 30 MeV incident neutron energy and associated covariances are needed in modern evaluated libraries, e.g., ENDF/B-VII.1, CIELO. Efforts are ongoing at LANL to provide these quantities.

For this evaluation, it is critical to have a good understanding of the fission process and of the shortcomings of experimental data and model predictions. In this contribution, the experimental data for the ^{239}Pu PFNS are briefly reviewed and open questions are outlined. Auxiliary experimental data, e.g the average total kinetic energy as a function of incident energy, which are of interest to constrain model input parameters, are also discussed.

We present improvements made to the original Los Alamos model (LAM), parameterizations used to derive model input parameters dependent on the incident neutron energy and extensions necessary to capture the physics involved in the post-scission part of the fission process. For instance, the pre-equilibrium contribution to the PFNS is considered in the PFNS modeling of this evaluation in addition to the contribution from multiple-chance fission neutron emissions. Realistic incident energy dependences of LAM input parameters such as the average energy release or the average total kinetic energy have been implemented.

These parameterizations of input parameters provide correlations between PFNS at different incident energies, which are essential to infer information from experimental data at lower incident energies to those energy ranges with scarce experimental information.

Preliminary evaluated results obtained by including the improved model information are shown. We conclude with an overview of possible physics beyond the assumptions of the LAM, e.g. scission or pre-scission neutrons.

Conference Dinner Special Guest

John C. Browne

Director Emeritus, Los Alamos National Laboratory

Recent developments in fission product yield evaluation

Robert Mills

UK National Nuclear Laboratory

The production of fission product yield evaluations for the computer simulation of reactors, fuel cycles and waste management is a well established field, however current techniques are dependent upon significant measurements of fission product yields for important fissioning nuclei in specific neutron energy spectra. Recent developments in modelling and measurement techniques offer the potential to significantly improve these evaluations. New models offer the potential to estimate fission product yields across a wide range of fissioning nuclei and neutron energy based upon a relatively small set of general parameters. In addition, new experimental techniques utilizing novel detector systems and analysis techniques offer the potential to rapidly expand the available sets of measured data and probe the energy dependence of fission yields.

The inclusion of these new data and models in evaluations offer potential improvements for applications, and utilizing these new more comprehensive models and measured data will allow a more quantitative estimate for many yields and a more rigorous uncertainty analysis resulting in covariance matrices for uncertainty propagation in spent fuel inventory calculations.

This talk will describe the recent work in this area being carried out within the WPEC sub-group 37 and within the recent EURATOM ANDES project.

The SOFIA experiment

Julien Taieb

CEA, DAM, DIF, F-91297, Arpajon, France

SOFIA (Studies On FIssion with Aladin) is an innovative experimental program on nuclear fission data measurements. The first experiment was successfully performed in august 2012 at the GSI facility. The fission of neutron-deficient actinides and pre-actinides was induced in flight by Coulomb excitation in a heavy material target. Complete isotopic yields (nuclear charge and mass) were measured over a broad range of fissioning nuclei. Despite low statistics for very neutron-deficient pre-actinides around mass 200, evidence for a transition from symmetric to asymmetric fission was found. For systems with high statistics and thanks to the performance of the SOFIA setup in terms of mass resolution, the number of prompt neutrons emitted during fission and the total kinetic energy were derived on an event-by-event basis, thus allowing the study - for instance within an isotopic chain - of the different fission modes. Finally, some information will be given regarding our forthcoming short run in october this year.

First Results of Fission Mass Yield Measurements with SPIDER at LANSCE

Krista Meierbachtol

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The new SPIDER detector at the Los Alamos Neutron Science Center (LANSCE) has been developed to measure fission product yields with high resolution as a function of incident neutron energy and product mass, charge, and kinetic energy. The robust capability of SPIDER to measure correlated fission product properties over an extended range of excitation energies will provide vital information as input to calculations and simulations, for comparisons to sophisticated fission models, and for application based data interpretation. The prototype SPIDER spectrometer has been assembled and the individual measurement components have been tested successfully. First results for 1E-1v measurements of spontaneous fission of ^{252}Cf and thermal neutron-induced fission of ^{235}U will be presented. Ongoing detector and data acquisition upgrades aimed at achieving the mass resolution goal of one atomic mass unit with a 2E-2v measurement will also be discussed.

This work is supported by LANL Laboratory Directed Research and Development Projects 20110037DR and 2012200077DR. LA-UR-14-24011.

Nucleon-Induced Fission Fragment Angular Distributions and the Reaction Mechanism

Lou Sai Leong

Japan Atomic Energy Agency

Fission fragment angular distributions exhibit generally a strong anisotropy, which varies steeply with the incident neutron energy above hundred keV.

This results from the combination of the spin and its components along the fission axis and along the beam direction, and this gives thereby information on the spin deposition mechanism and the structure of transitional states.

Recently, the ^{232}Th FFAD data have been measured at n_TOF at CERN, taking advantage of the very broad energy spectrum of the neutron beam.

Parallel Plate Avalanche Counters (PPAC) have been used to track the fission trajectory by detecting the 2 fragments in coincidence and a self-determination method has been applied to correct for the detection efficiency.

In the case of ^{232}Th, the result is in good agreement with previous data below 10 MeV, including the vibrational states which show a strong dip in anisotropy around 1.6 MeV. In the 14 MeV region, our data are much accurate than previous ones which are broadly scattered.

In addition, above 40 MeV our anisotropy data are lower than the single existing data. We will show that our values are in full agreement with the statistical model and follow the fissility systematics of nucleon-induced fission. In this framework the significant difference between proton- and neutron-induced fission is well understood.

This outcome sheds light on the spallation mechanism at 40 MeV, showing that the neutron is captured most of the time with a limited preequilibrium emission, as already inferred from the systematics of linear momentum transfer.

Fission Barriers and Fission-Fragment Yields in the region $170<A<330$

Peter Möller

Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Our approach is based on the macroscopic-microscopic method. We discuss briefly the advantages of this method relative to current versions of the HFB approach. We present calculated fission barriers for more than 5000 nuclei. The results are benchmarked with respect to several different types of experimental data: fission-barrier heights, electron-capture and beta-delayed fission, prompt-neutron-capture process, and spontaneous fission in the heavy-element region. We discuss the implications of the calculated results for the termination of the rapid-neutron-capture process.

The calculated five-dimensional potential-energy surfaces serve as a starting point for fission-fragment yield calculations based on the Brownian shape-motion model. We discuss 1) benchmarks of this method, 2) what it predicts about mass yield in the neutron deficient Pb region, where a new type of asymmetric fission has been observed, and how it agrees with the sparse data available there, and 3) a treatment of odd-even staggering based on this method.

Fission yield calculations with TALYS+GEF in the fast and high energy range and comparisons to experimental data

Stephan Pomp[1], A. Al-Adili[1], A. Koning[2,1]

[1] Division of Applied Nuclear Physics, Uppsala University, Uppsala, Sweden
[2] Nuclear Research and Consultancy Group, Petten, The Netherlands

The GEF code developed by Karl-Heinz Schmidt and Beatriz Jurado is considered to be the best currently available fission model code. Using only about 50 parameters, observables such as pre- and post-neutron emission fission yields as a functions of mass, charge and neutron number, average number of emitted neutrons (nubar), nu(A,Z), prompt fission neutron and gamma spectra, etc., for a large number of fissioning systems can be calculated. GEF can run as stand-alone version but has recently also been integrated into the nuclear reaction model code TALYS. TALYS handles the pre-fission stages; the excitation energies and the fission probabilities for all residual nuclei, i.e., the handling of multi-chance fission. The GEF code is used to calculate the pre-neutron emission yields and their excitation energy distributions. Currently work is on-going to allow for looping over the fission fragments and depletion of the excitation energy grids inside the same TALYS run. In this way post-neutron emission fission yields, nu(Z,A), nubar, prompt fission neutron and gamma spectra, etc., using the full Hauser-Feshbach and pre-equilibrium models of TALYS is possible.

We present results from the latest TALYS+GEF code for various systems and comparisons to evaluated data libraries. We compare in particular calculations to experimental data for (n,f) in the fast and high-energy region for Th-232, U-234 and U-238.

The Excitation Energy Dependence of the Total Kinetic Energy Release in $^{235}U(n, f)$

Walter Loveland

Department of Chemistry, Oregon State University, Corvallis, Oregon 97331, USA

The total kinetic energy release in the neutron induced fission of ^{235}U was measured (using white spectrum neutrons from LANSCE) for neutron energies from $E_n = 3.2$ to 50 MeV. In this energy range the average post-neutron total kinetic energy release drops from 167.4 $\pm$ 0.7 to 162.1 $\pm$ 0.8 MeV, exhibiting a local dip near the second chance fission threshold. We discuss the reason for this decrease. The values and the slope of the TKE vs. E_n agree with previous measurements but do disagree (in magnitude) with systematics. The variances of the TKE distributions are larger than expected and apart from structure near the second chance fission threshold, are invariant for the neutron energy range from 11 to 50 MeV. We also report the dependence of the total excitation energy in fission, TXE, on neutron energy.

Investigation of ^{238}U Fission Properties at LANSCE

Dana Duke

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The goal of this work is to measure the average total kinetic energy release ($\overline{TKE}$) and mass yield distributions in fission at high incident neutron energies for ^{238}U. Most of the energy released in fission goes into the kinetic energy of the fission fragments. Additional $\overline{TKE}$ information at neutron energies relevant to energy- and defense-related applications provides a valuable observable to benchmark simulations, as few measurements currently exist. The $\overline{TKE}$ and mass data are also employed in conjuction with fission models to improve understanding of the fission process. The Los Alamos Neutron Science Center - Weapons Neutron Research (LANSCE-WNR) facility provides a beam of neutrons with energies from hundreds of keV to hundreds of MeV. A double Frisch-gridded ionization chamber measures the energy and angle of the coincident fission fragments. This information is used in the double energy (2E) method to calculate fission fragments masses. Results of mass calculations and $\overline{TKE}$ for ^{238}U will be presented. LA-UR-14-25943.

Dynamical model for fission-fragment properties

Arnie Sierk

Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

We present a dynamical model of low-energy fission of actinides and other heavy nuclei. We solve five-dimensional Langevin equations for the nuclear shape as a function of time. The potential-energy surface is defined by the macroscopic-microscopic model, while the inertia is that of a scaled liquid drop. The initial dissipation model is a scaled version of the surface-plus-window model. We use distributions of starting conditions defined by the statistical mechanics of normal-mode dynamics at the saddle point. For spontaneous fission, we define from the potential energy surface a distribution of exit points from the barrier at which to start dynamical calculations.

Despite the relatively simple models for the inertia and dissipation, and a potential-energy model determined primarily by fits to nuclear masses, we find a satisfactory prediction of the fragment mass distribution and the average fragment kinetic energy in thermal-neutron-induced fission of ^{235}U. In addition to masses, the model predicts fragment kinetic energies, and the distribution of excitation energy between the fragments.

Progress with STEFF and Neutron-induced Fission

Gavin Smith

Department of Physics and Astronomy, The University of Manchester, M13 9PL Manchester, United Kingdom

The SpectromeTer for Exotic Fission Fragments (STEFF) is a 2E-2v device. It allows measurement of the velocities and energies of both fragments from the fission event. Mass may be measured either independently in each arm (Ev), or, by ignoring the momentum and kinetic energy contributions of the emitted fast neutrons and target effects, by the 2E or the 2v methods. STEFF also includes an array of 12 (5'x4') NaI scintillation detectors for gamma detection and is used in conjunction with the Manchester array of NE213 fast-neutron detectors. The fission fragments stop in two Bragg detectors the output of which are digitized as a function of time. The digitized traces may be used to measure energy loss (dE/dx) and range of the fission fragments. Data taken at the ILL, Grenoble in the reaction $^{235}\mathrm{U}(n, f)$ will be discussed along with plans for the use of STEFF at the new EAR2 station at nTOF, CERN.

Prompt X-Rays from Fast-Neutron-Induced Fission of ^{238}U

Ron Nelson

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Prompt K x-ray yields following fission induced by neutrons on ^{238}U have been measured for incident energies ranging from 1 to 400 MeV using GEANIE at LANSCE. The x rays are produced by internal conversion in the fission fragments following prompt neutron emission. The x-ray data are used to investigate the evolution with incident neutron energy of the fragment Z distribution and the x-ray emission probability per element. A progressive increase of the symmetric fission probability with increasing incident neutron energy is observed in qualitative agreement with Wahl systematics for fission fragment charge yields. Accurate estimates of charge yields can be calculated if sufficient nuclear structure and decay information is available.

Fission yield measurements at IGISOL

Andreas Solders

Division of Applied Nuclear Physics, Uppsala University, Uppsala, Sweden

Fission yield data is a key parameter in the design and operation of nuclear power plants. More accurate data could improve both safety and fuel economy of present generation reactors as well as that of future nuclear systems. Improved knowledge of isomeric fission yields are also important for simulations of the astrophysical r-process.

The Accurate fission data for nuclear safety (AlFONS) project aims at high precision measurements of fission yields, using the renewed Ion Guide Isotope Separator Online (IGISOL) facility in combination with a new high-current light-ion cyclotron at the University of Jyváskylá. Fission can be induced in an actinide target either directly by the 30 MeV proton beam or by a neutron field from a Beryllium converter target. Through a series of elements, culminating with the JYFLTRAP Penning trap, the fission fragments can be mass separated at a resolving power of a few hundred thousand.

We will here present the experimental setup and the IGISOL technique as well as some preliminary data from a measurement of the fission yield of proton-induced fission in Thorium. Also preliminary results from a measurement of isomeric yield ratios of proton-induced fission in natural Uranium will be discussed.

Prompt γ-ray spectroscopy of fission fragments

Nikolaos Fotiadis

LANSCE-NS, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

There is a long history of studies of fission fragments by identifying the prompt discreet lines they emit. This is especially useful in the study of neutron-rich nuclei and nuclei near stability. Generally, these nuclei cannot be studied as evaporation residues in heavy-ion fusion reactions because they cannot be populated with stable beam-target combinations in such reactions. Neutron-rich nuclei are usually studied by prompt γ-ray spectroscopy of fragments from spontaneous fission sources or light-ion or neutron-induced fission of actinide targets using modern γ-ray detector arrays, while in nuclei near stability fusion-fission reactions forming much heavier compound nuclei are preferred. Several examples, including recent results are invoked to illustrate the power of prompt γ-ray spectroscopy of fission fragments.

Index of Authors