FIESTA 2017
School & Workshop
Book of Abstracts

FIssion ExperimentS and Theoretical Advances

Santa Fe, New Mexico, USA, Sep. 17-22, 2017

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Fission Cross Section Experiments (lecture)

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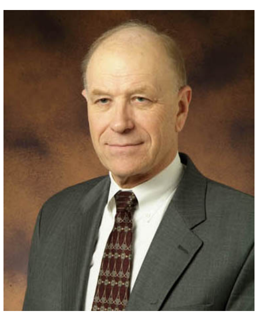
The complexity of the fission process leads to a very large number of observables that must be measured in order to improve our understanding of the underlying physics and to contribute to nuclear data needed in a wide array of applied programs. Measurements range from relatively straight-forward neutron cross sections to neutron and gamma ray multiplicities, fission fragment yield curves and beyond. This lecture will focus on fission cross section and fission cross section ratio experiments beginning with a historical perspective showing how such measurements have evolved from the first work to the present. It will briefly review experimental facilities and describe techniques illustrated by typical results. Some less-common methods of determining fission cross section data will be presented. The lecture will conclude with an overview of the state-of-the-art experimental facility that will be visited at LANSCE - the fission cross section Time Projection Chamber.



Dr. Lisowski is a Guest Scientist in the Associate Directorate for Experimental Physical Sciences at Los Alamos. He received his PhD from Duke University and joined the Los Alamos laboratory as a Staff Member in 1977. His career at Los Alamos involved research in areas ranging from neutron-induced fission to neutron diagnostic measurements on underground nuclear explosions to searches for parity violation. After retiring from Los Alamos as the LANSCE Director, Dr. Lisowski joined the DOE Office of Nuclear Energy as Deputy Assistant Secretary for Fuel Cycle Management where he was responsible for research and development of used nuclear fuel recycling technologies, fast reactor design, and advanced reactor fuel design and testing.

Theory and Modeling of Nuclear Fission Cross Sections (lecture)

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Nuclear fission cross sections are of crucial importance to nuclear astrophysics, nuclear engineering, and National security applications. The first theory of fission cross sections was adapted from quantum chemistry to the fission process in 1939 by Niels Bohr and John Wheeler. Modern versions of the "transition-state theory" introduced by Bohr and Wheeler have become the de facto standard used in virtually all reaction codes such as TALYS, EMPIRE, GNASH, STAPRE, etc. In these lectures I will review reaction theory covering the descriptions of scattering, resonances, and compound-nucleus formation, leading up to transition-state theory and its application to fission cross sections. I will also discuss research directions in obtaining fission cross sections from more microscopic approaches based on protons, neutrons, and their effective interactions.

Dr. Walid Younes is a staff scientist in the nuclear theory and modeling group at the Lawrence Livermore National Laboratory. He received his PhD from Rutgers University in 1996 and joined the LLNL nuclear experiment group soon after, performing γ-ray spectroscopy and cross-section measurements with actinides using the GEANIE spectrometer at LANSCE/WNR. From 2002 to 2005, he developed a program with Dr. H. C. Britt to extract fission cross sections using the surrogate reaction method, which closely combines modeling with experimental data. In 2006, Dr. Younes began developing a microscopic description of the fission process with Dr. D. Gogny. He is currently writing a research book on the microscopic theory of fission, and a graduate textbook on fission.

Poster Session

Fission Cross Section with a Time Projection Chamber

(Practical Session)

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Analysis of experimental data from a fission cross section measurement. We will use data collected in an experiment at LANSCE to go over some of the steps needed to determine fission cross sections. The analysis will include neutron time-of-flight calibration, and corrections for background events.

Fredrik Tovesson is a scientist and deputy group leader in the LANSCE Weapons Physics group at Los Alamos National Laboratory. Fredrik received a PhD in nuclear physics from Orebro University in 2003, and joined LANL as a postdoctoral researcher in 2004. His research focuses on nuclear fission, and he works on several projects related to fission cross sections and yields. He is currently involved with high precision fission cross section measurements with the NIFFTE Time Projection Chamber (TPC) and fission yield measurements with the SPIDER fragment spectrometer.

Kyle received is PhD in Nuclear Physics from the University of Tennessee in 2011. He joined the Laboratory as a postdoctoral associate in 2016 after serving as a Detector Physicist at ORTEC and as a postdoctoral associate at Oak Ridge National Laboratory and the University of Tennessee.

The Neutron Induced Fission Fragment Tracking Experiment: High-precision Fission Cross Section Measurements with a Time Projection Chamber

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The goal of the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) is to measure fission cross sections with very high precision. The NIFFTE Collaboration has designed and built a Time Projection Chamber (TPC) for this purpose. The 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 studied in detail, particularly those relating to fission fragment detection efficiency, particle identification and target and beam spatial uniformity. For example, the wealth of data captured for every fission event allows us to build and validate a detailed Monte Carlo efficiency model that must include effects such as anisotropy, fission fragment energy degradation, and target thickness, composition, and roughness. Here we present the current status of the NIFFTE TPC, describe the wide variety of systematic studies being performed, and outline recent results from measurements performed at the Los Alamos Neutron Science Center (LANSCE) facility.

Neutron-Induced Fission Measurements at the CERN n_TOF Facility

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Along with the study of radiative neutron capture reactions, measurements of neutron-induced fission cross-sections relevant for nuclear technology have been one of the two major components of the scientific programme at the CERN n_TOF (neutron Time-Of-Flight) facility since the commissioning of its 185m flight-path in 2001. Taking advantage of the high instantaneous neutron flux and high energy resolution, measurements have been performed on several long-lived major and minor actinides, from ^{232}Th to ^{245}Cm. The recent commissioning of a second experimental area at the end of an 18m flight-path has expanded the measurement capabilities to even more rare or short-lived isotopes. A description of the facility and of the detection systems used for fission measurements is given along with a review of past results and future measurement plans.

Neutron Cross Section Evaluation of ^{238}U

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The evaluations of neutron-induced reaction cross sections for ^{238}U are presented in neutron energy region from unresolved resonance region to 20 MeV. The model calculations have been performed by using the up-to-date nuclear reaction code, EMPIRE-3.2 which is a modular system of nuclear reaction codes. The coupled-channel optical models were parameterized in order to reproduce the available measurements such as cross sections of elastic angular distributions as well as total and elastic cross sections. DWBA was employed to improve the inelastic cross sections and its dynamic deformation values are parameterized to reproduce the measurements of neutron spectra as well as inelastic cross sections. The prompt nu-bar was produced through a least square fit and the prompt fission spectra calculated by the PFNS module using Los Alamos model implemented in EMPIRE.

The evaluated file was processed to data with point-wised cross sections by the NJOY code and tested to the criticalities for reactors recommended by International Criticality Safety Benchmark Evaluation Project (ICSBEP).

Measurement of the ^{234}U(n,f) at CERN n_TOF

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The ^{234}U(n,f) fission fragment angular distribution (FFAD) and cross section have been experimentally measured in the n_TOF facility at CERN using Parallel Plate Avalanche Counter (PPAC) detectors. This facility is characterized by a continuous neutron beam from thermal to GeV, produced by 20 GeV proton-induced spallation reactions in a lead target, with an energy resolution of ΔE/E = 5.3 10^{-3} for neutrons of 1 MeV due to the 185 m distance between the spallation target and the experimental area (EAR-1).

The FFAD results obtained in the full angular range (from 0° to 90°) up to 300 MeV are presented in this work. This is the first experimental measurement provided above 15 MeV, allowing to resolve the third-chance fission, and also the only experimental measurement provided in the full energy range from 100 keV to 300 MeV. The FFAD is anisotropic above 100 keV, and has to be precisely measured to correct the detection efficiency in the setups where it depends on the emission angle of the FF, for this reason, the detection efficiency has been corrected in this work using FFAD experimental results.

Current evaluations of the ^{234}U(n,f) fission cross section are mostly based on the experimental data measured by James et al. [1], and JENDL-4.0 also includes the experimental data measured by Heyse et al. [2] of the first resonance. The ^{234}U(n,f) fission cross section has been measured in this work from eV up to 1 GeV using the ^{235}U(n,f) reaction as reference. Higher resolution cross sections than the experimental data used in the evaluations are provided in the Resonance Region (RR), confirming the existence of two resonances in the Resolved Resonance Region (RRR) which are not evaluated in some libraries and, in addition some Class-II resonances are observed in the URR, where the evaluations provide an averaged value of the cross sections. In the threshold region, some resonant-like structures were observed in the work of James et al., which existence was confirmed by the experimental data measured by Paradela et al. [3] although the resolution was insufficient to resolve them, these structures, which were claimed to correspond to .-vibrational levels in the second well of the fission barrier, are resolved in fine detail by the present cross section data. In the fast energy region, where large anisotropies are found in the fission-chance thresholds, some discrepancies have been observed between the experimental data provided in EXFOR [4]. The present results have been obtained in this region using an accurate calculation of the detection efficiency including the experimental results of the FFAD.

In order to provide a theoretical description of the cross sections in the RR, the experimental results have been analyzed using the code CONRAD, the preliminary results are presented in this work.

[1] G. D. James et al., Phys. Rev. C, 15, 2083 (1977).

[2] J. Heyse et al., Nucl. Sci. Eng., 156, 211 (2007).

[3] C. Paradela et al., Phys. Rev. C, 82, 034601 (2010).

[4] EXFOR (Experimental Nuclear Reaction Data). http//www-nds.iaea.org/exfor/exfor.htm.

Investigation of the Surrogate Reaction Method via Simultaneous Measurement of Fission- and Gamma-Emission Probabilities of ^{240}Pu

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The surrogate-reaction method is an indirect way of determining cross sections for reactions that proceed through a compound nucleus. This method was first proposed by J. D. Cramer and H. C. Britt 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 depend 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.

In previous experiments, fission and gamma-emission probabilities, obtained with surrogate-reactions, were compared to the corresponding neutron-induced reaction ones. A strong discrepancy was seen between the gamma-emission probabilities, but this was not the case for fission. This difference of sensitivity in each case to what was the compound nucleus formation mechanism has not been fully understood. For this reason the CENBG group, in collaboration with the CEA-DAM, started a few years ago a campaign of experiments in which fission and gamma-emission probabilities are measured simultaneously. In April 2017 the group performed an experiment to investigate the ^{240}Pu(^{4}He,^{4}He') reaction as surrogate for ^{239}Pu+n. The ^{240}Pu is of special interest because as an even-even nucleus it is expected to be more sensitive to the spin and parity effects on the fission probability. Therefore the results of this experiment will help to improve our understanding on the surrogate reaction method.

In this contribution we will describe the experimental technique, the data analysis and the first results of this measurement.

The nELBE Neutron Time-of-Flight Facility

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The nELBE neutron time-of-flight facility provides neutrons in the energy range from about 10 keV up to 10 MeV with an intensity of about 10^4 n/s/cm^2. The combination of the superconducting electron accelerator ELBE and a compact liquid lead neutron production target delivers neutron bunches within a time spread of a few picoseconds and a repetition rate of 100 to 400 kHz (cw) enabling high resolution time-of-flight measurement even with flight paths of only 5 to 11 meters.

At nELBE different types of fast neutron induced nuclear reactions can be and have been investigated, ranging from total neutron cross section measurement over elastic and inelastic scattering to neutron induced fission.

E.g. the neutron induced fission cross section of ^{242}Pu has been measured in the range from 0.5 to 10 MeV relative to ^{235}U(n,f) using two fission ionization chambers. A statistical uncertainty down to 1.1% and systematic uncertainty of about 2.7% was reached.

Theory Investigations of Fission Fragment Yields (lecture)

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Fission product yields (FPY) quantify the probability of observing any given pair of fragments after a fission event. Together with the characteristics of the fission fragments themselves, they are essential inputs to simulations of the fission spectrum. From a theoretical perspective, fission product yields can be computed by simulating the time evolution of the fissioning nucleus from a compact shape to a configuration with two separated fragments. This is often done by assuming that fission is a slow process compared to intrinsic excitations of the nucleus. The consequence of this hypothesis of adiabaticity is that the dynamics of fission can be decoupled from the calculation of the static deformation properties of the fissioning nucleus. Different models are used to describe either the static properties or the time evolution itself. This lecture will present the two most commonly used combinations: the macroscopic-microscopic approach to nuclear structure coupled with stochastic Langevin dynamics and the nuclear density functional theory coupled with the time-dependent generator coordinate method. I will explain how FPY can be extracted from these theories. Overall the predictive power of the adiabatic theory remains of the order of 20-30% on prompt FPY. More recently, several groups have reported the first realistic, non-adiabatic real-time simulations of single fission events. While not yet applicable to calculations of FPY, these approaches are promising since they would include dissipation effects and give a more accurate representation of the scission mechanism, and I will briefly introduce them.

Dr. Nicolas Schunck is a staff scientist in the nuclear data and theory group at Lawrence Livermore National Laboratory. Nicolas received his PhD in nuclear theory in 2001 from the University of Strasbourg, France. He then went on to do postdocs at the University of Surrey (UK), Universidad Autonoma de Madrid (Spain) and the University of Tennessee. He has been working at LLNL since 2010 on the development, computational implementation and applications of nuclear density functional theory (DFT) methods, especially in the context of fission theory. Nicolas is currently the lead developer of the two DFT solvers HFBTHO and HFODD that are widely used to model properties of atomic nuclei both for basic nuclear science or astrophysical simulations. He is also strongly involved in several large collaborations of nuclear theorists: he coordinates DFT work in the NUCLEI collaboration funded by the SciDAC program of the US Department of Energy, and he leads the FIRE topical collaboration in nuclear theory.

Experimental Description of Fission Fragment Yields (lecture)

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Fission fragment yields are an important observable of the process, as they are the result of a multi-dimensional elongation of the nucleus. They are also the witnesses of structural effects (shells, pairing) on a macroscopic process. Their theoretical description is therefore a challenge, as a good reproduction of the yields is witness for a good understanding and prediction of the different nuclear states that lay in between the formation of the compound nucleus and the scission point, as well as the dynamics at which they are reached. However, if theoretical description of fission fragment yields is able to reproduce the gross properties of fission yields, fine predictions remain much too often difficult to match the observations. Beyond the computational and theoretical difficulties, this frustrating situation is caused by the difficulties to extract complete information on the scission point, the fragment-separation point, as well as on the exact sharing on protons and neutrons. Because of this inexactness, theoretical assumptions have difficulties to get validated and improved, despite 70 years of intense research on the topic. In this lecture, we will describe the principle of the fission-fragment yields detection, the main results that have been and are currently achieved. The experimental limitations to reach scission description and isotopic ratio of the fragments will be developed in terms of detection resolution and atomic-charge exchanges in the energy-loss process of fragments. The lecture will conclude on the opportunities brought about by fission studied at accelerator facilities.

I am a nuclear physicist, working in the field of nuclear reactions. I started with the population of high-spin states in fusion reactions, then moving to higher energy, I studied spallation reactions using inverse kinematics for the measurement of isotopic distribution of spallation residues. I have been fascinated by fission for more than one decade. In particular on the effect of pairing in fission yields and the fission yields themselves. I am working in GANIL, France, where I develop my experimental programme dedicated to the measurement of fission fragments using inverse kinematics at Coulomb energies. I believe that the new techniques brought about by accelerators and new spectrometer technologies will strengthen significantly the understanding of nuclear fission.

Poster Session

Cumulative Fission Product Yields for ^{235}U (practical session)

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Measuring Cumulative Fission Product Yields by Activation with Quasi-Monoenergetic Neutrons and Whole Target Gamma-Ray Counting. We will look at recent experimental fission product yield data and use it to determine several cumulative fission product yields. We will be analyzing gamma-ray spectra, making a normalization for the flux and considering several pitfalls that can occur in the analysis.

Matthew Gooden received his doctorate in Nuclear Physics from North Carolina State University in 2014 and is currently a postdoctoral research associate at LANL. His doctoral work at TUNL involved measuring cumulative fission product yields using monoenergetic neutrons. He continues to make energy dependence measurements of fission product yields, as well as, using nuclear techniques to the diagnosis of inertial confinement fusion implosions at the National Ignition Facility at Lawrence Livermore National Laboratory.

Gencho Rusev is a staff scientist in the Nuclear and Radiochemistry group at Los Alamos National Laboratory. After completing his PhD at Technical University Dresden, Germany, he joined Triangle Universities Nuclear Laboratory as a postdoctoral research associate in 2007. He then came to LANL as a postdoc in 2011. He worked in the area of nuclear structure and statistical gamma-ray properties using heavy-ion, photon- and neutron-induced reactions. Gencho's current research focuses on neutron capture and neutron-induced fission studies with the detector array DANCE.

Nuclear Fission in a Real-Time Density Functional Theory Approach

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Two major recent developments in theory and computational resources created the favorable conditions for achieving a microscopic description of nuclear fission almost eighty years after its discovery in 1939 by Hahn and Strassmann. The first major development was in theory, the extension of the Time-Dependent Density Functional Theory (TDDFT) to superfluid fermion systems. The second development was in computing, the emergence of powerful enough supercomputers capable of solving the complex systems of equations describing the time evolution in three dimensions without any restrictions of hundreds of strongly interacting nucleons. Even though the available nuclear energy density functionals (NEDFs) are phenomenological still, their accuracy is improving steadily and the prospects of being able to perform calculations of the nuclear fission dynamics and to predict many properties of the fission fragments, otherwise not possible to extract from experiments, are within reach, all without making recourse anymore to uncontrollable assumptions and simplified phenomenological models.

Dynamical Microscopic and Macro-Micro Approaches to Nuclear Fission

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Nuclear fission is a unique large-scale collective motion of nuclei which gives rise to a transition from a single to two (or rarely three) nuclear clusters. It is unique indeed in many facets: 1) it is important both in fundamental and application fields, 2) many different observables come out, which must be understood or explained in a consistent manner, such as isotopic and total kinetic energy distributions of fission fragments, emission of prompt neutrons and photons, then weak-decay of the resultant neutron-rich nuclei follows which will emit delayed neutrons, electrons, antineutrinos and photons, 3) quantal effects such as shell and pairing effects, which are tiny addition to the huge macroscopic energy in terms of a macro-micro view, dominate the fission process in many important nuclei such as U and Pu, 4) reactor antineutrino anomaly is offering a challenge to the standard model, 5) it is important to understand the origin of medium to heavy nuclei in astrophysical nucleosynthesis (NS-NS merger scenario), and so forth. In spite of a long history of research, however, understanding of the fission mechanisms, especially the part from the compound nucleus to scission point is still very poor. It is poor also in terms of the fact that predictions of the nuclear theory is not accurate enough to be used in application fields.

We have been doing a comprehensive approach to understand and describe the whole process of nuclear fission, where we use a dynamical macro-micro model (Langevin) as well as microscopic theories such as AMD and TDHF, and phenomenological statistical decay models. We wish to present and discuss problems we are facing with, our recent progress and ways to go.

Dynamical Fission Model

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Finally, 79 years after the experiments which uncovered nuclear fission were performed, a physical model has been developed which can make qualitatively and quantitatively accurate predictions about fission-fragment mass and energy distributions. This effort builds upon the revolutionary developments in the macroscopic-microscopic model for nuclear structure and binding energy developed by Nix, Nilsson, and Moller since 1970. I will outline the physical ingredients and the assumptions underlying this model and show some results for selected actinide isotopes, with comparisons to data. I will address possible routes to further improvements in accuracy and predictive power.

Fission Dynamics with Microscopic Level Densities

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The energy dependence of fission fragment yields is of great current interest. We have developed a general theoretical framework for addressing this issue within the Brownian treatment of nuclear shape dynamics. Taking advantage of a recent method for calculating the nuclear many-body level density on the basis of the single particle levels in the deformed mean field, we have calculated the shape-dependent nuclear level density for a number of nuclei of particular interest (each one requires more than five million shapes) and then used these to guide the Brownian motion of the nuclear shape as it negotiates the multi-dimensional potential-energy surface from the compact shape of the initial compound nucleus towards scission.

This method has no new parameters as it employs the same levels that were used to calculate the microscopic terms in the potential energy surface and it automatically accounts for the gradual disappearence of pairing and shell effects as the energy is raised. An appealing aspect of this new approach is the combination of microscopic structure properties with the classical shape dynamics. One particularly interesting finding is that the evolution of the fragment mass distribution need not be monotonic with energy: For example, we find that the symmetric yield exhibits a local minimum as a function of excitation and we trace this counter-intuitive behavior to the effect of the pairing correlations in shapes near the second barrier (where the shell effects are small); this is consistent with recent experimental data by Tonchev et al.

Fragment Distributions of Transfer- and Fusion-Induced Fission in Inverse Kinematics. The Impact of the Excitation Energy

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Transfer- and fusion-induced fission in inverse kinematics was proven to be a powerful tool to investigate nuclear fission, widening the information of the fission fragments and the access to unstable fissioning systems. An experimental campaign for fission investigation has being carried out at GANIL with this technique since 2008. In these experiments, a beam of ^{238}U, accelerated to 6.1 MeV/u, impinges on a ^{12}C target. Fissioning systems from U to Cf are populated through transfer and fusion reactions, with excitation energies that range from few MeV up to 46 MeV. The use of inverse kinematics, a silicon telescope, and the VAMOS spectrometer permitted the characterization of the fissioning system in terms of mass, nuclear charge, and excitation energy, and the isotopic identification of the full fragment distribution. The neutron excess, the total neutron multiplicity, and the even-odd staggering in the nuclear charge of fission fragments are presented as a function of the excitation energy of the fissioning system. Structure effects are observed at Z$\sim$50 and Z$\sim$55, where their impact evolves with the excitation energy.

Isotopic Distribution of Fission Fragments Using Multi-Nucleon Transfer Reactions in Inverse Kinematics

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Inverse kinematics is a new tool to study nuclear fission. Its main advantage is the possibility to measure with an unmatched resolution the atomic number of fission fragments, leading to new observables in the properties of fission-fragment distributions. In addition to the resolution improvement, the study of fission based on nuclear collisions in inverse kinematics benefits from a larger view with respect to the neutron-induced fission, as in a single experiment the number of fissioning systems and the excitation energy range are widen. With the use of spectrometers, mass and kinetic-energy distributions may now be investigated as a function of the proton and neutron number sharing. The production of fissioning nuclei in transfer reactions allows studying the isotopic yields of fission fragments as a function of the excitation energy. With the access to kinematics properties, the charge polarization of fragments at scission is now revealed with high precision, and it is shown that it cannot be neglected, even at higher excitation energies. Results on fissioning systems ^{238}U, ^{239}Np, ^{240}Pu, ^{244}Cm, obtained in transfer reactions are presented, together with the fusion reaction leading to the compound nucleus ^{250}Cf at an excitation energy of 45 MeV.

Fission-Fragment Studies Using γ-Ray Spectroscopy

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Identifying fission fragments using detection of the discrete γ rays they emit during de-excitation is a powerful tool in the study of the nuclear structure of neutron-rich nuclei and nuclei near the stability line. There is a long history of such studies, especially for nuclei that cannot be studied as evaporation residues in heavy-ion fusion reactions because they cannot be populated with stable beam-target combinations in such reactions. Usually, neutron-rich nuclei are 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. The population of nuclei near stability is, generally, stronger in fusion-fission reactions forming much heavier compound nuclei. Several recent results will be presented to illustrate the power of such studies.

Short Lived Fission Product Yield Measurements in ^{235}U, ^{238}U and ^{239}Pu

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Yields of short lived fission products (FPYs) with half lives of a few minutes to an hour contain a wealth of information about the fission process. Knowledge of short lived FPYs would contribute to existing data on longer lived FPY mass and charge distributions. Of particular interest are the relative yields between the ground states and isomeric states of FPYs since these isomeric ratios can be used to determine the angular momentum of the fragments. Over the past five years, a LLNL-TUNL-LANL collaboration has made precision measurements of FPYs from quasi-monoenergetic neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu [1]. These efforts focused on longer lived FPYs, using a well characterized dual fission chamber and several days of neutron beam exposure. For the first time, this established technique will be applied to measuring short lived FPYs, with half lives of minutes to less than an hour. A feasibility study will be performed using irradiation times of < 1 hour, improving the sensitivity to short lived FPYs by limiting the buildup of long lived isotopes. Results from this exploratory study will be presented, and the implications for isomeric ratio measurements will be discussed.

[1] M. Gooden et al. Nucl. Data Sheets. 131, 319 (2016).

Visit to the Los Alamos Neutron Science Center

Theory of Neutron and γ Emission in Fission (lecture)

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By following the time dependence of neutron emission during the fission process, three different types of neutron emission can be considered: the 'pre-fission neutrons' which are emitted prior to the fission in multiple-chance fission, the 'scission neutrons' (their existence is still controverted into the physicist community) which could be emitted when the neck rupture of the fissioning nucleus occurs (scission point) and lastly the 'prompt neutrons' which correspond to neutrons evaporated by the excited fission fragments. For each type of emission, the mechanism will be described. Since 'prompt neutrons' constitute by far the main source of the neutron emission, several approaches used for describing their energy spectra and multiplicities will be detailed as well as their correlations with the fission fragment characteristics (mass, kinetic energy, ...). During the de-excitation process of the fission fragments, prompt gammas can also be emitted (sometimes in competition with prompt neutrons). Their main properties (energy spectra, multiplicities and angular distributions) will be also discussed. Following the prompt particle emission, fission products are in general unstable and undergo beta-decay. For some of them (called precursors), neutrons and gammas are accompanying the beta-decay process and are referred as 'delayed neutrons' and 'delayed gammas'. Due to the importance of these delayed particles for nuclear energy applications, their characteristics will be briefly mentioned.

Dr. Olivier SEROT has received his PhD in nuclear physics in 1992 from the University of Bordeaux (France). Then, during 5 years, he was involved at the 'Institute for Reference Materials and Measurements' at Geel (Belgium) in experimental activities related to the fission cross section measurements and the determination of the ternary particles characteristics (energy spectra and emission probabilities). A theoretical model for ternary particle emission process was also developed. In 2000, he became permanent physicist at the Nuclear Energy Directorate of the French Atomic Energy Commission (Cadarache/France). He initiated a new collaboration with the Institute Laue Langevin (Grenoble/France) and the Laboratory of Subatomic Physics and Cosmology (Grenoble/France) in order to measure isobaric, isotopic and isomeric fission yields using the LOHENGRIN mass spectrometer for various fissioning systems. More recently, he has participated to the development of a new Monte Carlo code dedicated to the simulation of the fission fragment deexcitation, capable of predicting prompt particle characteristics and correlations between fission observables.

Experimental Measurements of Prompt Fission Neutrons and γ Rays (lecture)

Franz-Joseph Hambsch
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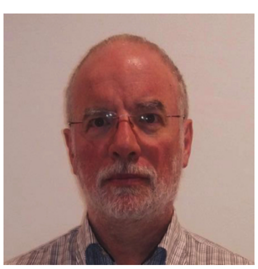
EU-JRC, Geel, Belgium

Measuring prompt neutron and gamma-ray emission is a challenge in nuclear fission research. Concerning prompt neutrons not much progress has been made in terms of detector developments. Still nowadays, neutron detectors are mainly based on NE213 equivalent liquid scintillator material in combination with photomultipliers. Recent progress in neutron measurements has to be attributed to the implementation of digital data acquisition techniques and respective digital signal processing algorithms. In addition to measure correlations with fission fragments novel position sensitive charged-particle detectors were developed and applied in array-type detector systems like SCINTIA. Concerning prompt gamma-ray detection a lot of progress has been made in recent years in detector development. The availability of gamma-ray detectors based on cerium-doped lanthanide-halide crystals has given a boost to new investigations. Those detectors have much better timing properties, a better energy resolution and higher efficiency as compared to previously used NaI:Tl based detectors. Also here, the additional use of digital signal acquisition and processing techniques led to substantially improved results. During the lecture the fundamentals on how to measure prompt fission neutron and gamma ray spectra (PFNS, PFGS) will be highlighted, the difficulties mentioned and the progress demonstrated.



Dr. Franz-Josef (Josch) Hambsch is a Senior Scientists at the European Commission, Joint Research Centre in Geel, Belgium, formerly known as the Institute for Reference Materials and Measurements (IRMM). His extensive experience and expertise lies in the field of nuclear fission physics. He works on projects related to the identification of prompt neutron and gamma-ray emission in correlation with fission fragments. He has also gained experience in light-charged particle and actinide fission cross section measurement as well as with related theoretical modelling.

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Analysis of FREYA and CGMF – Correlated Fission Modeling

(Practical Session)

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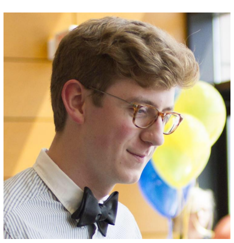
We will analyze output from the FREYA and CGMF fission event generators, and in particular study correlations in prompt fission neutron and γ-ray emission results.

Ramona Vogt got her PhD in nuclear theory at the State University of New York at Stony Brook. She joined LLNL in 2007 where she is a member of the nuclear data and theory group at LLNL. She is also an Adjunct Professor at UC Davis. She is an internationally recognized nuclear theorist with more than 100 published papers and 75 conference proceedings and has been an organizer of many international workshops and conferences. She is the co-developer of the complete Monte Carlo fission model FREYA (Fission Reaction Event Yield Algorithm) with Jorgen Randrup of LBNL. Together they have written numerous papers on FREYA, including several with experimental collaborators, and, along with Jerome Verbeke of LLNL, have published FREYA in Computer Physics Communications. She is actively involved in the American Physical Society, having been a member of the Executive Committee for the Topical Group on Hadronic Physics since 2008. She became a Fellow of the APS in 2010 and an APS Outstanding Referee in 2016. She has been an organizer of Nuclear Science Day for Girl and Boy Scouts at LBNL since 2011. When not doing physics, she is likely out running on trails.



Jackson is a student at UC Berkeley studying physics. Recently he has worked with the FREYA fission event modeling algorithm. In particular he has been investigating the benefits and trade-offs of using stochastic optimization.

Study of the Prompt Neutron Multiplicity in the $^{236}U(\gamma,f)$

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SOFIA (Studies On Fission with Aladin) is an experimental set-up, which allows to fully identify both fission fragments in coincidence. It is located at GSI, the only place to use inverse kinematic at relativistic energies in order to study the (γ,f) electromagnetic-induced fission.

The first aim of this experiment is to accurately measure the fission yields. This will be detailed, as well as the set-up used, during the poster session on the fission fragment yields. Since both fission fragments and the fission nucleus are isotopically identified, the SOFIA experiments provide, event-per-event, an indirect measurement of the total neutron multiplicity. Moreover, taking advantage of the correlation between both fission fragments masses, the neutron multiplicity as function of the mass number of the primary fragments ν(A) is deduced from a numerical analysis.

This talk will briefly reminds the reaction mechanism used, which produces a compound nuclei with an excitation energy, in average, about 14 MeV. Then, the measurements on the total mean neutron multiplicity will be presented. Finally, the numerical analysis leading to ν(A), and the results obtained for the coulomb-induced fission of ^{236}U, will be detailed and compared to some $^{235}U(n_{\rm th}, f)$ direct kinematics measurements.

Prompt Neutron Emission in the Reaction ^{235}U(n, f)

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Experimental activities on prompt neutron emission in fission at JRC-Geel in response to OECD/NEA nuclear data requests are presented in this contribution. Investigations of prompt neutron emission of importance in understanding the fission process in general and the sharing of excitation energy among the fission fragments in particular. The focus of this contribution is on investigations of the reaction ^{235}U(n,f) in the region of the resolved resonances, performed at the GELINA facility. For this reaction strong fluctuations of fission fragment mass distributions and mean total kinetic energy as a function of incident resonance-neutron energy have been observed [1]. In addition, small fluctuations of prompt neutron multiplicities have also been reported in the literature [2]. The goal of the present study is to verify the current knowledge on fluctuations of PFN multiplicity and fission fragment properties, as well as to study correlations between the properties of prompt neutrons and fission fragments. The experiment employs the scintillation detector array SCINTIA for neutron detection, while fission fragment properties are determined via the double kinetic energy technique employing a recently developed position-sensitive twin ionization chamber.

[1] F.-J. Hambsch et al., Nucl. Phys. A 491 (1989) 56
[2] R. E. Howe et al., Phys. Rev. C 13 (1976) 195

Measurement of High-Energy Prompt γ Rays from Neutron-Induced Fission of ^{235}U(n, f)

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Prompt fission γ-ray spectra (PFGS) are important as they allow us to study the structure and de-excitation process of neutron-rich fission fragments. They are also required as nuclear data to design new types of reactors, such as the Generation-IV reactors. For spontaneous fission of ^{252}Cf, the PFGS show a hump structure associated with a giant dipole resonance (GDR) observed in fission fragments around 15 MeV. For neutron-induced fissions, however, no data are available in the energy range higher than 7 MeV. With a goal to measure the PFGS for neutron-induced fission of ^{235}U up to energies of 20 MeV, we have developed a new measurement system. The system consists of two position-sensitive multi-wired proportional counters (MWPCs) to detect both fission fragments in coincidence, and two large volume LaBr3(Ce) scintillators to measure the gamma-rays in fission. The measurement has been carried out at the PF1B cold-neutron facility of the Insitut Laue Langevin (ILL), Grenoble, France. The obtained PFGS reached about 20 MeV, high enough to reveal the structure associated with the GDR of the FFs, for the first time in neutron-induced fissions. In this contribution, we will present the details of the experimental method and results obtained the measurement.

Prompt γ Rays from the Spontaneous Fission of ^{252}Cf and their Angular Distribution

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Extreme Light Infrastructure - Nuclear Physics (ELI-NP)

Nuclear fission is a complex process, which, after almost 80 years since its discovery, is still not fully understood. One field of research is for instance studies of the de-excitation process of fission fragments, which in the early stages, i.e. within a few nanoseconds after scission, takes place through the successive emission of prompt neutrons and γ rays. For nuclear applications, information about the prompt neutrons is crucial for calculating the reactivity in reactors, while precise knowledge about the prompt gamma rays is important for the assessment of the prompt heat released in the reactor core. Concerning the latter we have contributed in the past years with a number of precise measurements of prompt γ-ray spectra from spontaneous as well as thermal and fast neutron-induced fission of various compound systems. From those we determined average characteristics like multiplicity, mean energy per photon and total γ-ray energy released in fission.

The obtained results were investigated for their dependences of mass and atomic numbers of the fissioning system as well as the dissipated excitation energy. The purpose of this endeavor was to find a description that allows predicting prompt γ-ray spectra characteristics for cases that cannot be studied experimentally.

In this study we report on a recent measurement of prompt fission γ rays from the spontaneous fission of ^{252}Cf, in which we even measured angular correlations between these γ rays and the fission fragments detected in coincidence. We will present first preliminary results and infer what can be learned from the observed angular distributions. For instance, the relative contributions of dipole and quadrupole radiation among the prompt fission γ rays were deduced and compared to the results of very recent calculations with the Monte Carlo code FIFRELIN, developed at CEA Cadarache.

High Energy Prompt Fission Neutron Spectrum Measurements for the Spontaneous Fission of ^{252}Cf Using a Multiple Gamma Tagging Method

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Previous measurements have been performed at RPI measuring the prompt fission neutron spectrum of ^{252}Cf in the energy range from 50 keV to 7 MeV using the multiple gamma tagging method. Smaller sample mass and short flight-path prevented this measurement from having useable data in the energy range above 7 MeV and therefore and new experiment was planned focusing on the high energy range. This range is particularly important since even in the standard evaluation by Mannhart uncertainties can be as large as 10% in this energy region. The multiple γ tagging method relies on the high γ multiplicity from fission in order to determine the timing of the fission event. A coincidence of two on an array of four BaF_2 detectors is used to determine the fission event timing for time of flight measurements. This multiple γ tagging method is advantageous over both fission chamber methods and single γ tagging method particularly in the high energy range. The higher γ penetrability compared to fission fragments allows for much larger samples to be used which greatly improves the counting rate for the low probability high energy γs. Additionally, when compared to single gamma tagging there is much lower background and much greater timing resolution with the multiple γ tagging method providing more accurate measurements at high energy. Measurements are currently being performed at RPI to measure the prompt fission neutron spectrum in the energy range from 1 MeV to 16 MeV and preliminary results show good agreement with previous measurements and evaluations.

Preliminary Results from the Triple Fission-Ejecta Correlations Trial (TRIFECTA) at ORNL

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Despite fission having been studied for almost 80 years, there is a shortage of data on the correlations of multiple fission products needed to benchmark advanced theoretical models of fission. A pioneering experiment underway at ORNL, the Triple Fission-Ejecta Correlations Trial (TRIFECTA), involves the measurement of energy and angular correlations between prompt ^{252}Cf fission neutrons and γ rays with respect to one fission fragment in time-coincidence. The mass of one fragment is determined, with 4 amu precision, by using 2 micro-channel plate timing detectors and a silicon total-energy detector. Time-coincident data from auxiliary detectors are also recorded: 6 NaI detectors to measure γ-ray multiplicity, 1 HPGe detector to measure the high-resolution γ-ray spectrum, and an array of 28 VANDLE modules to measure the neutron spectrum and multiplicity. For the first time, correlations between coincident fragment-gamma-neutron fission products can be studied, as a function of fragment mass. Utilizing certain unique γ-ray transitions recorded by the HPGe detector, we were able to determine the neutron energy and angular correlations of specific fission fragments. Preliminary results on neutron$-$neutron angular correlations, γ-ray vs. neutron multiplicity, and other correlations will be presented, along with plans for future improvements.

Work supported in part by the Laboratory Directed Research and Development Program of ORNL, managed by UT-Battelle, LLC, for the U.S. Department of Energy.

Quantifying the Impact of Theoretical Fission Yields on Prompt Particle Observables

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Recently, fission fragment yields have been calculated from macroscopic-microscopic models for a variety of fissioning systems and found to show good agreement with experimental measurements. We test the impact of using these theoretically-calculated mass yields on the eventual prompt neutron and gamma observables. This is done by modeling the de-excitation of the fission fragments with a Hauser-Feshbach statistical decay framework. We draw connections between the characteristics of the mass yields and prompt particle observables. Our results demonstrate that even small discrepancies between experimental and theoretical mass yields can result in deviations from prompt particle observables, such as the prompt neutron multiplicity, outside the allowed errors, providing useful constraints.

Chi-Nu Measurement of ^{235}U and ^{239}Pu Prompt Fission Neutron Spectra

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The prompt fission neutron spectra (PFNS) from the neutron-induced fission of major actinides play an important role in criticality measurements, global security, and nuclear reactor design and also provide stringent tests of nuclear physics models. Research on any of these topics relies on nuclear data evaluations that are, in turn, based on experimental data. Despite the importance of the PFNS from major actinides, there are not many measurements over the entire incident neutron energy range of interest. Furthermore, many of the measurements that do exist do not agree with each other within the quoted 1-σ uncertainties, thereby complicating nuclear data evaluations. High-precision measurements of the PFNS are needed to improve and validate nuclear data evaluations and to progress the above-mentioned fields.

The Chi-Nu experiment at the Los Alamos Neutron Science Center (LANSCE) has recently taken high-statistics data on the PFNS from ^{235}U and ^{239}Pu. Results will be presented for the ^{235}U PFNS as well as preliminary results for the ^{239}Pu PFNS. Details of data analysis including a discussion of analysis methods and uncertainty quantification will be provided.

MCNP – a Review of our 70-Year History, Current Status and Upcoming Future (lecture)

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The Monte Carlo method for radiation particle transport has its origins at LANL dating back to the 1940s. The creators of these methods were Drs. Stanislaw Ulam, John von Neumann, Robert Richtmyer, and Nicholas Metropolis. Monte Carlo methods for particle transport have been driving computational developments since the beginning of modern computers; this continues today. In the 1950s and 1960s, these new methods were organized into a series of special-purpose Monte Carlo codes, including MCS, MCN, MCP, and MCG. These codes were able to transport neutrons and photons for specialized LANL applications. In 1977, these separate codes were combined to create the first generalized Monte Carlo radiation particle transport code, MCNP. In 1983, MCNP3 was released for public distribution to the Radiation Safety Information Computational Center (RSICC). The upcoming release of MCNP (version 6.2) is expected in June 2017. Approximately 20,000 copies of MCNP have been distributed to users in government institutions, academia, and private industries worldwide. This talk will review our history, current status, and future directions.

XCP-3 Monte Carlo Methods, Codes, and Applications Group Leader, Los Alamos National Laboratory, Los Alamos, NM. PhD. Nuclear Engineering N.C. State Univ. (2000). Currently, I am responsible for approximately 40 technical staff involved with Monte Carlo radiation transport methods and code development (including MCNP) and applications in nuclear criticality safety, passive and active radiation detection and measurement, nuclear threat evaluation and response, and nuclear experiment design and assessment. My previous technical work includes MCNP code development (physics and feature improvements, code modernization, verification, validation) and several projects focused on radiation detection and measurement, nuclear non-proliferation, warhead and treaty verification, nuclear emergency response, and nuclear counterterrorism. My previous academic contributions include adjunct faculty at four universities as co-advisor for seven PhD students and four post-doctoral students at LANL.

Application of Fission: Reactor Physics (lecture)

Jean-Christophe Sublet
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International Atomic Energy Agency, Vienna, Austria

The importance of fission cross-sections, energy dependence, prompt, delayed neutron multiplicities and spectra, fission products yields for typical reactor applications will be subject to scrutiny with emphasis on power reactor needs. Thermal, fast, pile or large power reactor core physics simulations based on nuclear fission, requirements in terms of neutron balances (production, disappearance and leakage) are rather specifics but also bounding. They have tremendous impacts on the power plants design, operability and safety aspects during their entire lifetime. Fissions processes, their significances, interpretation through simulations viewed from a reactor physics perspectives will be presented.

Dr.-Eng. Jean-Christophe Sublet has been recently appointed nuclear data services unit head of the International Atomic Energy Agency in Vienna. Prior to this latest post, he was covering the management and technical leadership of the work performed by the UKAEA on the provision and development of the next generation, 21st century multi-particles, multi-physics, multi-scale, source terms and inventory simulations systems and technology driven nuclear data library able to foster the nuclear and material sciences renaissance. He has been a lead evaluator of nuclear data: EAF, TENDL; developer of the processing code CALENDF, inventory code FISPACT-II. Jean-christophe in his career has worked for AREVA, CEA, UKAEA and now the IAEA on the nuclear data and neutronics aspects of most types of nuclear devices.

Safeguards Applications of Nuclear Data (practical session)

Cameron Bates and Madison Andrews

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Los Alamos National Laboratory

Our exercise will show students the impacts of nuclear data on nuclear safeguards measurements. They will extract a “new” evaluation for fission properties and then see how that changes the assay of unknown material.

Cameron Bates is a staff scientist in XCP-3 at Los Alamos National Laboratory. Cameron received his BSE in Nuclear Engineering and Radiological Sciences from the University of Michigan in 2010. He went on to pursue a PhD in Nuclear Engineering at the University of California, Berkeley. He performed his PhD research at Lawrence Livermore National Laboratory working on ultra-high resolution gamma-ray spectroscopy for nuclear safeguards applications. Cameron received his PhD in May 2015 and took a postdoc position in XCP-3. He has since become a staff scientist in the group working on arms control and stockpile stewardship problems.

Madison Andrews received her Bachelor’s in Engineering Physics from Queen’s University in 2009. She completed her Master’s and PhD in Nuclear Engineering at the Royal Military College of Canada in 2011 and 2015, respectively. She came to Los Alamos National Laboratory as a Director’s Postdoctoral Fellow in 2015 and was recently converted to a staff scientist. Her current research is on safeguards radiation detection capabilities with the Monte Carlo Codes and Safeguards Science and Technology groups at LANL.

OpenMC: an Open-Source Monte Carlo Code for Neutron Criticality Simulations

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This talk will introduce the OpenMC code project, key features of the code and recent research developments in the area of nuclear data processing. OpenMC is an open source Monte Carlo code that was developed primarily for reactor criticality simulations on leadership class computing platforms with additional features and applications being added continuously. The code is hosted on github and counts developers form multiple universities and national laboratories. Amongst the key features that will be discussed are the on-the-fly Doppler broadening of cross sections via the windowed multipole formalism, continuous material tracking for seamless integration with other physics packages, and recent developments in uncertainty quantification from resonance parameters.

Diagnostic Imaging Using Contrast from Fission

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In this presentation, a number of approaches that have been developed or are under development at Oak Ridge National Laboratory for imaging the distribution of either spontaneous or induced fission sites in items containing or consisting of special nuclear materials (SNM) will be described and, where available, experimental results will be shown. Fission is readily induced or occurs spontaneously in only a small number of materials, such as SNM, whose accurate accounting and characterization are of interest to safeguards, treaty verification, and homeland security.

Historically, measurements of fission-neutron emanations from SNM have served as a key diagnostic for its non-destructive assay because fission neutrons readily penetrate high atomic number materials and because attributes of fission neutrons, such as their number and correlation, can be related to characteristics of the inspected items containing SNM. However, interpretation of bulk-counting (non-imaging) data can be ambiguous when assessing configurations that are complicated or include multiple sources. In these instances, imaging approaches can be useful, and can potentially reduce or eliminate ambiguity in confirmation or characterization measurements. The ability to form an image is enabled by the ability to associate a measurable quantity, such as a number of neutrons, with a path through an inspected object, or "line of response." Lines of response having contrast for fission can be accomplished via either collimation of detected neutrons or collimation of interrogating neutrons and subsequent detection of induced neutrons. Instruments and methods based on each of these principles will be described, and will include:

1. A tomographic imager for $\sim$55 gallon drums that performs three-dimensional transmission and induced-fission imaging. This instrument is based on interrogation using 14-MeV neutrons from the $d + t \rightarrow \alpha + n$ reaction, where "collimation" is accomplished by knowing the initial trajectory of the neutron by detecting the associated alpha particle. In analogy to conventional multiplicity counting, a fraction of the induced fissions are detected by counting one or more neutrons in coincidence in fast organic scintillation detectors. However, in contrast to conventional multiplicity counting, the number of fissions is increased by the interrogating source and the initiation times of fission chains are known by correlation to the times of interrogation by source neutrons.

2. A passive fast neutron emission imager (currently under development) that is intended to perform imaging of the fast fission neutron emissions from individual fuel pins in spent nuclear fuel assemblies. This instrument is based on a novel collimator that enables trans-axial tomographic imaging in order to verify the integrity of fuel assemblies.

Evidence of σ-χ-ν Correlations in Evaluated Data Files

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The most recent generations of evaluated nuclear data files exhibit excellent integral performance (as shown by the good agreement between experimental and calculated K_{eff} values for a wide range of benchmark experiments). However, the propagation of the uncertainties associated with these evaluated nuclear data to integral observables generally produces calculated distributions which are much (3-5 times) wider than the experimental uncertainties of the experiments. Reducing the variances of the evaluated data to achieve consistency would lead to unreasonably narrow variances compared to those of microscopic differential experimental data. One way of solving that paradox can be to allow, for different observables like the fission cross sections (σ), the prompt fission neutron spectra (χ), and the average multiplicities of fission neutrons (ν), to be correlated, in a Bayesian-like, Total Monte-Carlo approach, under integral constraints. Examples will be shown for σ-χ-ν correlations of ^{239}Pu evaluated nuclear data, under constraints from some PMF (Plutonium Metallic Fast) integral experiments from the ICSBEP benchmark compilation. Future developments will be highlighted, and restrictions imposed by the formatting of nuclear data will be discussed.

Application of LANL Fission Models to the Astrophysical r-Process

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Atomic nuclei are one of the most multifaceted systems in the universe. The approach of studying these complex systems through the use of global nuclear models has been a cornerstone of LANL and proven insightful to a wide variety of applications. Our theoretical framework is based on the nuclear properties predicted by the Finite-Range Droplet Model (FRDM). For nuclear fission, reactions and branching ratios we utilize a combination of statistical Hauser-Feshbach (HF) as well as Quasi-particle Random Phase Approximation (QRPA). I focus my discussion on the application of these models to the astrophysical r-process; thought to be responsible for the creation of approximately half of the heavy elements above iron in the cosmos. The extension of our theoretical framework to nuclei at extreme neutron-excess allows for the calculation of relevant capture rates as well as neutron-induced fission and beta-delayed fission properties which are critical inputs for the r-process. I also discuss the ongoing progress being made with fission yields and their impact on the final abundances we observe in nature. This work has been supported by the FIRE (Fission In R-process Elements) collaboration.

Sensitivity Studies and MTAS Measurements for the Decay Heat Calculation

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In 2007 Nuclear Energy Agency of OECD published the report Assessment of Fission Product Decay Data for Decay Heat Calculation [1], containing the list of isotopes which beta-decay should be measured or remeasured in order to improve the agreement between calculation of the decay heat (DH) based on the experimental data and the available direct measurements. There are two approaches to calculate DH: one takes available fission yields and measured decay properties only, the other, in addition includes theoretical predictions for very exotic isotopes where experimental decay data do not exist or are clearly incomplete. In this work we compare these two types of calculations to look for the isotopes, which are responsible for the main differences between the results. For the first type of calculations we use our in-house developed program, while for the second type of calculations we use industry approved standard SCALE/ORIGEN [2], which gives much better agreement with the experimental data and not only includes the theoretical predictions for the unknown isotopes, but also for some relatively well studied isotopes uses different (up to 50%) values, than suggested by the evaluated data files [3][4]. In this work we will present our own inventory of isotopes for which different input parameters are used and therefore which may have the highest impact on the filling the gap between measured and calculated decay heat. We will also report on the recent study [5] on few of these isotopes performed by means of Modular Total Absorption Spectrometer.

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The Provision and Validation of Nuclear Data at AWE

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Reliable, validated nuclear data are a crucial component of the neutronics capability required to support AWE's programme of work. Work is performed by the Nuclear Data Team to evaluate existing data sources, process data in the formats used by AWE's multiphysics codes and validated by benchmarking to known experiments.

Sensitivity Analysis of ^{252}Cf(sf) Neutron and Gamma Observables in CGMF

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CGMF is a Monte Carlo code that simulates the decay of primary fission fragments by emission of neutrons and γ rays, according to the Hauser-Feshbach equations. As the CGMF code was recently integrated into the MCNP6.2 transport code, great emphasis has been placed on providing optimal parameters to CGMF such that many different observables are accurately represented. Of these observables, the prompt neutron spectrum, prompt neutron multiplicity, prompt γ spectrum, and prompt γ multiplicity are crucial for accurate transport simulations of criticality and nonproliferation applications. This contribution to the ongoing efforts to improve CGMF presents a study of the sensitivity of various neutron and gamma observables to several input parameters for Californium-252 spontaneous fission. Among the most influential parameters are those that affect the input yield distributions in fragment mass and total kinetic energy (TKE). A new scheme for representing Y(A,TKE) was implemented in CGMF using three fission modes, S1, S2 and SL. The sensitivity profiles were calculated for 17 total parameters, which show that the neutron multiplicity distribution is strongly affected by the TKE distribution of the fragments. The total excitation energy (TXE) of the fragments is shared according to a parameter R_T, which is defined as the ratio of the light to heavy initial temperatures. The sensitivity profile of the neutron multiplicity shows a second order effect of R_T on the mean neutron multiplicity. A final sensitivity profile was produced for the parameter α, which affects the spin of the fragments. Higher values of α lead to higher fragment spins, which inhibit the emission of neutrons. Understanding the sensitivity of the prompt neutron and γ observables to the many CGMF input parameters provides a platform for the optimization of these parameters.

The SOFIA Experiment: Measurement of the Isotopic Fission Fragments Yields

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SOFIA (Studies On Fission with Aladin) is an experimental set-up dedicated to accurate measurement of fission fragment isotopic yields. It is located at GSI, the only place to use inverse kinematic at relativistic energies in order to study the (γ,f) electromagnetic-induced fission. The SOFIA set-up is a large acceptance magnetic spectrometer, which allows to fully identify both fission fragments in coincidence, leading to the isotopic yields, mean neutron multiplicity and TKE measurements.

The first SOFIA experiment was performed in August 2012. During 6 days, a broad range of nuclei from ^{183}Hg up to ^{238}Np were produced by fragmentation and separated at the FRS (FRagment Separator) facility. A second measurement of 1.5 day with an upgraded set-up was performed in October 2014 to measure the yields of the ^{236}U fissioning nucleus. This poster will detail the set-up, and present some results on fission of uranium and thorium isotopes.

A New Era in Photo-Fission Measurements Initiated at ELI-NP

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The Extreme Light Infrastructure - Nuclear Physics facility, ELI-NP, a state-of-the-art laboratory dedicated to promote nuclear physics research with extreme electromagnetic fields, is expected to become operational in 2018. Along with a 10 PW high power laser system (HPLS), it will host a highly brilliant in-beam system (GBS) [1,2] delivering photon beams with high spectral density ($\sim 10^4$ photons/s/eV), high resolution (band width 0.5%) and high degree of linear polarization (>95%) [3]. This brilliant beams will allow precise photo-nuclear measurements in the 0.2-19.5 MeV energy range and will also overcome the existing limitations on photo-fission experiments carried out till date, hence opening a new era for high resolution measurements of sub-barrier transmission resonances in the fission decay channel with cross sections down to 0.1 eV b [4].

The photo-fission experimental campaign at ELI-NP mainly aims at measuring the absolute photo- fission cross section of actinide nuclei (^{232}Th, ^{238}U, ^{235}U, ^{244}Pu, to start with) with high precision, and to study the characteristics: energy, mass, charge and angular distributions, of the fission fragments as well as the ternary fission products using the high-intensity, quasi mono-energetic γ-ray beams produced at ELI-NP. The study of ternary photo-fission will become possible for the first time due to the high intensity of the ELI-NP beam. An important goal is to resolve the so-far unobserved fine structure of the isomeric shelf by decomposing it into individual transmission resonances, and to observe the predicted nucleon clusterization phenomena in super- and hyper-deformed states of the actinides [4]. The polarized beams provide an excellent opportunity to study the space asymmetry of the angular distribution of the fission fragments and the correlation between the space asymmetry and the asymmetry of the fission process [4,5].

In order to make these measurements possible, we are developing two new detector arrays based on existing, well-understood cutting-edge technologies. The first setup, called ELITHGEM, is an array of 12 thick gas electron multipliers (THGEM) inside a low-pressure gas chamber, dedicated to the measurement of cross sections and fission fragment angular distributions as a function of the photon energy. This detector array covers almost a full solid angle (around 80% of 4π) and has an angular resolution of about 5°. The second setup, called ELI-BIC, includes a set of four double-sided Frisch-grid Bragg ionization chambers to investigate the fission fragment characteristics. Each ionization chamber will be coupled with eight ΔE-E detectors (covering about one solid angle) for the study of ternary fission [4].

The present status of development of the above mentioned detector arrays will be reported along with the results from test experiments carried out to check the sensitivity and functionality of the detectors. The near future plans for in-beam test experiments at the existing neutron and in-beam facilities will also be presented along with our future plans for Day-One experiments with the ELI-NP beams.

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Fission Yield Calculations with the TALYS Code

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Nuclear data finds relevance in many applications. It is fundamentally important for analyses related to safety, licensing, waste management and decommissioning issues, astrophysics, nuclear medicine, as well as fundamental physics. The TALYS code is an open source modern computer system that provides opportunities to calculate a wide range of nuclear data quantities including the fission yields for actinides. In this work, we present the results of comparison of fission mass distributions calculated using the Brosa model and the GEF model which was recently incorporated into the code. The calculations have been performed for both pre and post neutron emission cases. The validation was done at differential level by comparing the calculated fission-fragment mass distribution to the experimental data taken from the data library. Additionally, it was shown the procedure of reaction cross section adjustment by means of nuclear model parameter variation.

Krypton Fission Product Yields from 14 MeV Neutron-Induced Fission of ^{238}U at the National Ignition Facility

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Precisely-known fission yield distributions are used to determine a fissioning isotope and the incident neutron energy in nuclear security applications. 14 MeV neutrons from DT fusion at the National Ignition Facility (NIF) induce fission in depleted uranium (DU) contained in the target assembly hohlraum. The fission yields of Kr isotopes (85m, 87, 88, 89, and 90) are measured relative to the cumulative yield of 88Kr. The fission gas is pumped from the target chamber, collected, and analyzed in the Radiochemical Analysis of Gaseous Samples (RAGS). Isotopes with half-lives ranging 8s−9hr can be measured. Kr fission yields have been measured both from the fission of DU in the hohlraum and DU doped into the capsule ablator. Since the mass of U is not known, the relative amounts of Kr isotopes are calculated and compared to existing fission product distribution tables. This measurement produces more precise results than those given in the evaluated data.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Measurements of Short-Lived Fission Isomers

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Fission yields of the short lived isomers ^{134m}Te ($T_{1/2}$=162 ns) and ^{136m}Xe ($T_{1/2}$=2.95 μs) were measured for ^{235}U, ^{238}U, and ^{239}Pu. The isomers were detected by the γ rays associated with the decay of the isomeric states using high-purity germanium detectors. Fission was induced using both monoenergetic γ rays and neutrons. At TUNL's High-Intensity Gamma-ray Source (HIγS), γ rays of 9, 11, and 13 MeV were produced. Monoenergetic 8 MeV neutrons were produced at TUNL's tandem accelerator laboratory. Both beams were pulsed to allow for precise time-gated spectroscopy of both prompt and delayed γ rays following fission. This technique offers a non-destructive probe of special nuclear materials that is sensitive to the isotopic identity of the fissile material.

Measurement of Intense Continuous and Flash Radiographic Sources with Compton Spectrometers

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Our team at Los Alamos National Laboratory has successfully employed Compton spectrometers to measure the x-ray spectra of intense radiographic sources, both continuous and flash. In this method, a collimated beam of x-rays incident on a convertor foil ejects Compton electrons. A collimator may be inserted into the entrance of the spectrometer to select the angular acceptance of the forward-scattered electrons, which then enter the magnetic field region of the spectrometer. The position of the electrons at the magnet?s focal plane is proportional to the square root of their momentum, allowing the x-ray spectrum to be reconstructed. Two spectrometers have been fielded since 2013; a neodymium-iron permanent magnet with an energy range of 500 keV to 20 MeV, and a new samarium-cobalt magnet with an energy range of 50 keV to 4 MeV. The measured spectra were produced by x-ray generating machines of various intensities ($\sim$5 rad at 1 m per 50 ns pulse to $>$2000 rad/min at 1 m) and different endpoints (range of 2.25 to 20 MeV). A survey of these results will be presented with emphasis on our recent, low-energy experiments.

Analysis of Recent Neutron Induced Fission from the NIFFTE fissionTPC

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The fissionTPC, built for the purpose of making neutron-induced fission cross section measurements with unprecedented precision, is a two-chamber MICROMEGAS time projection chamber that allows for three-dimensional tracking of charged particles. This three-dimensional tracking capability also provides a direct measurement of fission fragment angular distributions for neutron-induced fission. Fragment angular anisotropy is an important experimental observable for understanding the quantum mechanical state of the fissioning nucleus and a parameter required to determine detection efficiency for cross section measurements. Preliminary results for ^{235}U fission fragment anisotropy as a function of neutron energies in the range 130 keV $-$ 100 MeV will be presented.

Total Kinetic Energy and Fragment Mass Distributions from Fission of ^{232}Th and ^{233}U

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Properties of fission in ^{232}Th and ^{233}U were studied at the Los Alamos Neutron Science Center (LANSCE) at incident neutron energies from sub-thermal to 40 MeV. Fission fragments are observed in coincidence using a twin ionization chamber with Frisch grids. The average total kinetic energy released from fission and fragment mass distributions are calculated from observations of energy deposited and conservation of mass and momentum. Accurate experimental measurements of these parameters are necessary to better understand the fission process in isotopes relevant to the thorium fuel cycle, in which ^{232}Th is used as a fertile material to generate the fissile isotope of ^{233}U. This process mirrors the uranium breeder process used to produce ^{239}Pu with several potential advantages including the comparative greater abundance of thorium, inherent nuclear weapons proliferation resistance, and reduced actinide production. For these reasons, there is increased interest in the thorium fuel cycle to meet future energy demands and improve safety and security while increasing profitability for the nuclear power industry. This research is ongoing and preliminary results are presented.

Hunting for r-Process Signatures in the Galaxy

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There are roughly 25 very metal-poor (VMP: [Fe/H] < -2.0), highly r-process-enhanced (r-II: [Eu/Fe] > 1.0) stars currently known, discovered over the past quarter century. These stars, rich in neutron-capture elements, are vital in determining the astrophysical site(s) of the r-process, as they provide nearly pure signatures of r-process events early in the Galactic history. We are currently conducting a high-resolution follow-up survey on RAVE targets in order to identify a total of 100 r-II stars. Our pilot run on the du Pont 2.5-m telescope at Las Campanas Observatory, Chile, has already demonstrated success in identifying at least ten new r-II stars. We are continuing our high-resolution follow-up effort in order to better characterize the site(s) and nature of the r-process, including the actinide boost.

Induced Fission of ^{240}Pu in Time-Dependent Density Functional Theory

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The nuclear density functional theory (DFT) is the only microscopic theory that can be applied throughout the nuclear chart. Using its extension to time-dependent superfluid fermion systems, superfluid local density approximation (TDSLDA), we studied the induced fission of Pu240 in three-dimensional coordinate space without any symmetry restriction. By selecting different initial conditions on the potential energy surface of Pu240 with different energy density functionals (EDF), we obtained 44 fission trajectories and calculated various fission fragment properties (mass distributions, TKE, etc.). For these properties, the average values are very close to the measurement, while the fluctuations are highly suppressed.

Measurement of the ^{234}U(n,f) and ^{235}U(n,f) Fission Fragment Angular Distribution at CERN n_TOF

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In the measurements of fission cross sections, the detection efficiency has to be high accurately known. As the Fission Fragment Angular Distribution (FFAD) is anisotropic above 100 keV for both, ^{234}U(n,f) and ^{235}U(n,f) reactions, it has to be precisely measured to correct the detection efficiency in the setups where it depends on the emission angle of the fission fragments. However the FFAD data provided in EXFOR are limited up to 15 MeV for the ^{234}U(n,f), being barely known above 25 MeV for the ^{235}U(n,f). In addition, the FFAD is an important observable to investigate the nuclear fission process, specially in the fission-chances thresholds, where large anisotropies are observed for both reactions.

In order to measure the FFAD of neutron-induced fission reactions, a fission detection setup based on Parallel Plate Avalanche Counter (PPAC) detectors has been developed and successfully used at the CERN n_TOF facility. The ^{234}U(n,f) and ^{235}U(n,f) FFAD have been measured in this work using the tilted configuration of targets and detectors [1,2], which unlike the perpendicular configuration [3], allows to cover all the emission angles of the fission fragments.

Results on the analysis of the FFAD and anisotropy parameter up to 300 MeV are presented in this work, providing for first time data of the ^{234}U(n,f) above 15 MeV, and completing the existing measurements of the ^{235}U(n,f).

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Correlation in Prompt γ and Neutron in Fission

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Neutrons and photons are emitted during the fission process, when a heavy nucleus splits into two fragments, which are energetically excited. In the de-excitation process, multiple prompt neutrons and gammas are emitted in coincidence. A possible dependence between neutron and gamma multiplicity is investigated by analyzing collected data. An array of 45 liquid organic scintillation detectors and a fission chamber are used to describe event by event multiplicities. The experimental data is then compared to MCNPX-PoliMi simulations. The detected data is unfolded from the low efficiency response system to extract multiplicities at emission. These results are then used to predict the correlation between the multiplicities, in the form of a linear dependence.

FIRST RESULTS ON ^{238}U(n, f) PROMPT FISSION NEUTRON SPECTRA MEASUREMENT AT CHI-NU

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A new ^{238}U(n,f) prompt fission neutron spectra (PFNS) measurement has been recently performed at the WNR facility of the Los Alamos National Laboratory.

The measurement allowed us to explore the dependence of the prompt fission neutron energy spectra on the incident neutron energy, which covers the range from 1 to 200MeV.

The experimental setup couples the 54 Chi-Nu scintillator cells array to a newly developed fission chamber, characterized by an improved alpha-fission discrimination and time resolution, a reduced amount of matter in the neutron beam and a higher actinide mass.

The dedicated setup and the high statistics collected allowed us to obtain a good precision on the measured fission neutron energy, as well as to explore the low energy region, down to 500 keV, and the high energy region, above 5 MeV, of the emitted neutron spectrum. These are indeed the regions where discrepancies in the evaluated PFNS data are found.

In this contribution we will present the first results of the experiment, with a particular focus on the dependence of the multiplicity, the mean kinetic energy of the emitted neutrons and the temperature of the fissioning system as a function of the incident neutron energy up to few MeV.

Quasi-Differential Neutron-Induced Neutron Emission (QD-NINE)

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The nuclear industry, in both the commercial and government realms rely on accurate nuclear data and an understanding of the relevant physics. The Quasi-Differential Neutron-Induced Neutron Emission (QD-NINE) method compares accurate MCNP simulations to experimental data in order to assess the accuracy of evaluated nuclear data libraries. If discrepancies are found, the experimental data acts as a constraint in order to improve the evaluations.The primary goals of this work are to perform a QD-NINE analysis of ^{235}U and ^{239}Pu at the Weapons Neutron Research facility and enable future QD-NINE analyses within Los Alamos National Laboratory.

A test measurement of Carbon was performed in 2015 and a measurement of ^{235}U was performed in 2016. The preliminary results of the ^{235}U measurement show promise but suggest that additional work may be required to properly characterize the emission spectrum due to low count rates. This is due to the fact the the ^{235}U sample was a collection of smaller samples, each of which was encapsulated in a hydrogenous medium, greatly reducing the signal to noise ratio.

Both the Carbon test measurement and ^{235}U measurement show good agreement with their respective simulations.

Experiments are scheduled to be performed within this beam cycle at the Los Alamos Neutron Science Center (LANSCE) to improve upon the measurement of ^{235}U by using a single sample of greater mass, thereby reducing the total mass of encapsulation material and increasing the signal to noise ratio. It is planned to also measure ^{239}Pu during this time.

The Study of γ Emission in the Fission Process

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Prompt fission gamma spectra (PFGS) have been recently measured for the ^{238}U(n,f) and ^{239}Pu(n,f) reactions using fast neutrons produced by the LICORNE directional neutron source. The setup consisted of ionization chambers containing the actinides samples and $LaBr_3$ scintillation detectors, as well as a cluster of PARIS phoswich detector, to measure the coincident prompt fission γ rays. Prompt fission γ rays were discriminated from prompt fission neutrons using the time-of-flight (TOF) technique. The multiplicities, total energies per fission and average energies of photons were extracted from the PFGS. In addition, information on the dependence of PFGS characteristics as a function of excitation energy was obtained.

These experiments provide important nuclear data for reactor physics, as an input for γ heating calculations, since the γ heating effect can be under-estimated by up to 28% with present nuclear data. Furthermore the new PFGS information will be useful from a fundamental physics point of view, where results can be compared with many competing theoretical predictions to refine models of fission process. Observables like multiplicities, mean energies and total energy can shed light on the energy sharing between fragments and the angular momentum generation mechanism in fission process. It will also lead to a better understanding of the competition between neutron and γ emission.

Liquid-gas Coexistence Phase in Nuclear Matter

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Nuclear matter at low temperatures (T $\lesssim$ 15 MeV) exhibits liquid-gas transition phases and liquid-gas coexistence states for a variety of isospin content and density combinations. This phenomenon is well known and has been subject of numerous studies in the past decades. From the absence of a successful Equation of State (EOS) for nuclear systems, it arises a need for numerical approximations for the research of their properties. Previous inquiry established that bulk and thermodynamic properties of neutron rich nuclear matter can be investigated by means of Classical Molecular Dynamics (CMD). In this study, we present data obtained from CMD simulations and a method to determine a 3-dimensional phase diagram using these results, interpolation techniques, and Maxwell constructions. We performed more than 300 simulations of nuclear matter for settings of 2000 nucleons with isospin content X (Z/A) = 0.3, 0.35, 0.4, 0.45, 0.5 at temperatures of T = 1-5 MeV and T = 10-15 MeV, with densities between ρ=0.02 fm^{-3} and 0.18 fm^{-3}. Our results of pressure per nucleon as functions of the density for each system were stored and further analyzed to construct a phase diagram. From this study, we aim to extract the boundaries and shape of the liquid-gas coexistence region for neutron-rich nuclear matter, thus determining its intrinsic physical conditions.

Keywords: Liquid-gas phase transitions, Classical Molecular Dynamics, Maxwell Construction.

Target Characterization for 1% Cross Section Precision with a Time Projection Chamber (TPC)

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The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) collaboration has undertaken to measure the ^{239}Pu(n,f)/^{235}U(n,f) cross section ratio in the fast neutron energy regime with a total systematic uncertainty of 1%. To achieve this level of uncertainty, one important challenge is to measure the content of ^{239}Pu and ^{235}U target deposits to unprecedented precision. A low-geometry alpha counting setup has been constructed to benchmark the performance of the TPC in performing this measurement. Resulting uncertainties for both the TPC and the auxiliary counter are dominated by the uncertainties on alpha decay half-life inputs. This measurement validates the overall precision of the TPC for counting charged particles with high precision. Target characterization methods and results will be presented.

Updated β-Decay Study of Neutron-Rich ^{75}Zn into ^{75}Ga using LeRIBSS at HRIBF

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Recent study on beta decay of neutron-rich ^{75}Zn into ^{75}Ga is presented with updated decay scheme and structure of ^{75}Ga. The present study utilized a more efficient detector setup along with high purity of the ^{75}Cu beam in comparison to previous studies with present rate of over 2000 ions/s. The purity of beam used prevented any member of the decay chain from being dominant and allowed for comparisons of branching rations between the decays. The greater efficiency of the HPGe detector array meant detection of more low energy γ-ray from the decays. The γ-γ and β-γ coincidence data from the experiment were obtained at LeRIBSS and were used to develop a revised decay scheme.

The ^{240}Pu(n,f) Cross-Section Measurement at CERN's n_ToF New Experimental Area II (EAR-2)

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The accurate knowledge of the neutron-induced fission cross-sections of minor actinides and other isotopes involved in the nuclear fuel cycle is essential for the design of advanced nuclear systems, such as Generation-IV nuclear reactors, as well as for the reduction of safety margins regarding their operation. Such experimental data can also provide the necessary feedback for the adjustment of nuclear model parameters used in the evaluation process, resulting in the further development of phenomenological nuclear fission models.

In the present work, the ^{240}Pu(n,f) cross-section was measured at CERN's n_TOF facility relative to the well-known ^{235}U(n,f) cross section, over a wide range of neutron energies, from meV to a few MeV using the time-of-flight technique and a set-up based on Micromegas detectors. This measurement was the first experiment to be performed at n_TOF's new experimental area (EAR-2), which offers a significantly higher neutron flux compared to the already existing experimental area (EAR-1).

The data analysis has revealed, that resonances can be resolved up to at least a few tens of keV, that correspond to transitions between class-I and class-II states, which are not included in the latest evaluation libraries (i.e. ENDF/B-VII.1, JEFF-3.2, etc). In addition regarding the first chance fission plateau, analysis shows that there is a general agreement with current evaluation libraries and latest experimental data within a few percent, with the exception of a dip around 2.5 MeV, which is not included in the evaluations and is seen by a similar measurement performed in GNEIS facility.

Nearly final results and the analysis as well as the experimental details, are presented.

Neutron-Related Reactor Functions at Radiation Measurements Laboratory in the ATR Complex

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The ATR (Advanced Test Reactor) is located at Idaho National Laboratory (INL) site and has been operating continuously since 1967. The ATR is a uniquely designed enriched uranium, pressurized water moderated & cooled reactor with a serpentine-shaped core. The ATR is much smaller than commercially operating reactors, and it operates at lower temperatures, pressures and total power output. Its unique design allows to achieve much higher power density levels, temperatures and pressures at different locations depending on the experiment needs. The ATR has 77 irradiation positions in three different configurations: (1) as a simple static capsule, (2) instrumented lead experiment or (3) pressurized water loops. It is used for isotope production, fuel and material testing, material aging and speeding up a fission process, thus eliminating excessive long-lived radiation sources. This reactor is primarily operated by the US Navy, but it is currently designated as a 'National Scientific User Facility' to be used by universities, national laboratories and industry. It is also used in collaboration with foreign research program including some from South Korea, India and Japan.

The activities in the Radiation Measurement Laboratory (RML), which is located at the ATR complex, include some routine work for the reactor: monitoring of reactor's primary and secondary water system, ion exchange columns, resins, cations and anions concentration; as well as monitoring the stack emissions for particulates and gas exhaust from radioactive elements, during the reactor cycle and the outage. The RML also participates in the cobalt (Co-60) assay program for characterization of activated cobalt in the ATR canal. The gamma-ray dose is measured laterally within a dry tube in the ATR canal, before and after irradiation and compared to a standard. Another important activity is "flux monitoring" which is done by measuring the activation of Co-Al and Ni wires that are inserted in the holders located within the safety rod fixture. These wires are sensitive to thermal (Co) and fast (Ni) neutron flux in the probe during the activation cycle. This allows the determination of the thermal versus fast neutron fluence as a function of position in the reactor core.

The RML also supports the ATRC (Advanced Test Reactor Critical) facility, a low-power duplicate of the ATR, designed to test prototypical experiments before they are placed into the ATR. Fission rates are measured as a reflection of a total reactor power and its distribution within the reactor via irradiation of U-Al flux wires, sometimes with an additional activation foils, at selected positions of the reactor. The annual ATRC neutron level calibration and cobalt reactivity measurements are performed using cobalt, nickel and silver wires, where cobalt is used for thermal energy neutron analysis (0.025 meV), nickel for fast neutrons, > 1 MeV, and silver to measure standardized neutron activation rates associated with the calibration of the ATR N-16 power level monitoring system.

The RML laboratory provides not only monitoring of routine radiation safety operations and radioisotope production, but helps to establish and monitor fluxes and its dynamics due to location and thermal versus fast neutron rate. Our neutron flux analysis in the ATRC helps to plan the ATR for its final performance.

Fission observables from 3-D Langevin equation calculated with microscopic transport coefficients

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We summarize the progress made in 3-D Langevin calculations. We present the result of fission observables in comparison to 3-D Langevin calculations with macroscopic transport coefficients. These results include mass distributions, TKE distributions, TKE dependence on excitation energy and systematic behaviour of these observables. We also include some recent result on the contributions of pairing effects in microscopic transport coefficients on 3-D Langevin calculation.

Parameter Optimization and Uncertainty Quantification for the FREYA Code

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As both a standalone fission event generator, and as an algorithm implemented in transport simulations such as MCNP, it is important to assess the accuracy of the output with respect to existing data, as well as quantify the appropriate uncertainty associated with the observables of interest.

In particular, the set of parameters determining the nature of FREYA's output, can be tweaked to fit the data available in existing nuclear libraries, and the process of fitting these parameters can help to determine the sensitivity, and reliability of the output.

In particular I have used different methods of annealed variance, and other stochastic minimization procedures to produce such a set of parameters. This process returns a robust collection of statistics regarding both the optimization itself, and FREYA at large. This process accurately, and efficiently determines the reliability of FREYA.

Recent Results of Reverse Engineering Nuclear Masses from Solar r-Process Abundances and the Challenges Faced in the Presence of Fissioning Nuclei

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The astrophysical site(s) of the rapid neutron capture process (r-process) remains one of the most challenging open problems in all of physics. Conclusive statements are difficult to make due to a limited knowledge of nuclear physics far from stability. We describe recent developments in the method of 'reverse engineering' nuclear properties using well established observational data for the rare earth elements. This new theoretical framework is intended to be used in combination with recent and future measurements to gain new insights into the astrophysical site of the r-process. To do so we perform this procedure for a variety of astrophysical environments in order to differentiate between the trends in the mass surface required to fit the rare earth solar data. We present results for the most recent reverse engineering mass predictions given the astrophysical trajectory of a hot, low entropy wind and compare to the mass data for neutron rich neodymium isotopes recently measured at the CPT at CARIBU. Since fission properties of nuclei far from stability are experimentally unknown, neutron rich environments present challenges to the reverse engineering approach. We describe these challenges and the impact of fission properties, such as fragment yield distributions and fission rates, on the r-process abundance pattern.

A Fully Microscopic Approach for the Description of the Fission Process

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Nearly 80 years after the discovery of nuclear fission, its theoretical understanding from the basic constituents of the nucleus (protons and neutrons) and their interaction remains a challenge.

In this work, a fully microscopic approach is considered. It consists of two steps. In the first one, a set of static states is generated along two collective coordinates (mass elongation and mass asymmetry) using the finite range Gogny interaction. Afterwards, the states are mixed using the Time Dependent Generator Coordinate Method (TDGCM) without any approximation to obtain the time evolution of the nucleus during the fission process. The mass and charge yields for the reactions $^{235}\mathrm{U}(n_{\mathrm{th}}, f)$ and $^{239}\mathrm{Pu}(n_{\mathrm{th}}, f)$ are then estimated from this time evolution.

STEFF at n_TOF

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Measurements at the neutron time-of-flight facility n_TOF at CERN have been performed with the Spectrometer for Exotic Fission Fragments, STEFF to investigate the properties of neutron induced fission on ^{235}U. Within STEFF, a combination of timing and energy detectors for the fission fragments and inorganic scintillators for the gamma-rays allow information to be found on fragment mass, energy and charge in parallel with average prompt gamma-ray energies and multiplicities. The experiments were performed at n_TOF EAR2, a vertical neutron beam line with a flight path of approximately 18 m and a neutron energy range of meV - MeV. The performance of STEFF at n_TOF is reported along with recent developments and improvements.

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