Our Future Nuclear Data Needs

November 25, 2018

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# Introduction

## The two faces of nuclear data

Low-energy nuclear science (LENS), where sub-nucleonic degrees of freedom can be ignored, straddles the fence between curiosity- and application-driven pursuits. On the curiosity-driven side, low-energy (*Ex* < 1-4 MeV) nuclear structure offers a unique laboratory to examine the interplay between single-particle and collective behavior and to explore the transition from quantum to continuum behavior in a mesoscopic setting. LENS also plays an important supporting role in nuclear astrophysics, providing information necessary for accurately modeling stellar energy generation, as well as utilizing isotopic abundances in a manner similar to that of nuclear forensics, to inform models of the astrophysical environments where heavy nuclei are formed. On the application-driven side, well-quantified knowledge of low-lying nuclear structure and reactions is needed to model energy generation and isotope production for medical and industrial uses and national security and counter-proliferation communities.

One hallmark of LENS is that most theoretical descriptions are primarily descriptive rather than rigorously predictive at the level of accuracy and over the entire range of energies etc. needed for the applications listed above. As a result, targeted measurements are coupled to a nuclear data evaluation process (including post-publication review), created to use physically accurate modeling, guided by experimental information, to produce databases of recommended values that can be employed by the user communities. This work is carried out by a community that has similar components to other areas of physics, including theory, modeling, and experimental components. These individuals usually come from the LENS research community, but then go on to study for many years under experienced evaluators in order to develop the highly-specialized skills needed for the work.

This manuscript will start with a description of the nuclear data evaluation process, and the organizations organization that carry it out. It will then describe two important cross-cutting nuclear data needs that are important to multiple applications: fission and neutron transport on the “Big 3” actinides (235,238U and 239Pu), and improved information regarding continuum nuclear states for reaction modeling. Following this is a discussion of nuclear data needs for specific applications, including medical isotope production, nuclear energy, and national security/nonproliferation. It will then end with a discussion of the future of nuclear data, including the need to train the next generation of nuclear data evaluators and a new, Nuclear Data Interagency Working Group that has been formed to develop a national nuclear data plan to address high-priority needs for applied nuclear science and technology.

## The Nuclear Data Pipeline

The first step in improving nuclear data involves the use of carefully-designed measurements with well-defined uncertainties. Following publication, these results go through a post-publication evaluation process that merges them with other data sets and results in the creation of data libraries of use to the application communities.

The nuclear data evaluation process is comprised of four steps. The first, and potentially most important, of these databases is the Nuclear Science Reference file (NSR) [NSR]. NSR contains references to published works from major LENS journals as well as internal reports from labs throughout the world. NSR serves as the starting point for the data evaluation process. Descriptive keywords are assigned to these articles by individuals with LENS backgrounds, enabling the use of this information in later portions of the evaluation process.

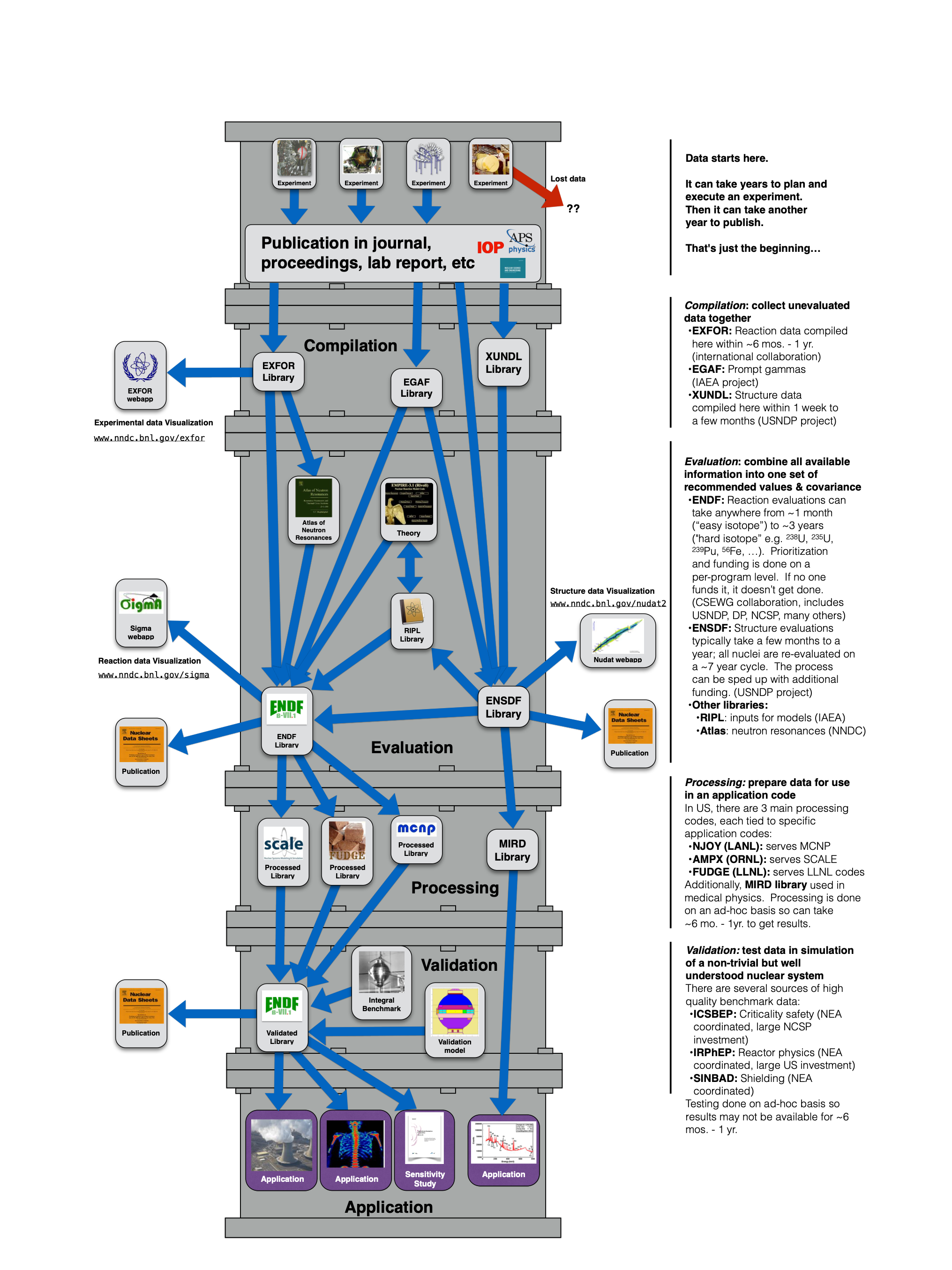
The next step in the evaluation process involves *compilation*. In this step the data from the primary references contained in NSR, including both mean values and uncertainties, are extracted in numerical form and assembled into one of two databases depending on whether the data are primarily regarding nuclear structure and decay, or nuclear reactions.

The nuclear structure compilation database is called the Experimental Unevaluated Nuclear Data List (XUNDL) [XUN]. The nuclear data in XUNDL is organized by nuclide, meaning that a single publication could lead to the production of more than one XUNDL dataset. Each XUNDL dataset is treated as a “stand-alone” work and is not required to agree with existing, evaluated nuclear data for the nuclide it concerns. However, during XUNDL compilation basic consistency checks are performed and any internal inconsistencies are pointed out to the author to allow them be reconciled in the database. XUNDL is used by both nuclear structure evaluators to aid in their work and by nuclear structure researchers as a quick way to access data from current publications in order to guide their own research. The vast majority of XUNDL compilation is performed by a handful of evaluators in the United States.

The nuclear reaction compiled database is referred to as the Experimental Nuclear Reaction Data library (EXFOR) [EXF]. This includes not only reaction cross sections, but also related data such as fission yields, resonance integrals, polarization data and more. Given the wide range of data types present in EXFOR there is little or no error checking performed during the compilation. However, an online visualization tool is provided to allow users to plot and manipulate the data. EXFOR is used by both nuclear reaction evaluators and the nuclear reaction research and application community.

The next step in the process is *evaluation* itself. In the case of nuclear structure data this involves reconciling multiple types data sets (e.g., prompt gamma and particle spectra, decay data, etc.) and deriving a recommended set of adopted values. This data forms the basis of the Evaluated Nuclear Structure Data File (ENSDF) [ENS]. While most of the ENSDF evaluation is performed in the US, there is a significant and growing component coming from evaluators throughout the world. The governing body that determines the rules for the evaluation process is the Nuclear Structure and Decay Data Network administered by the International Atomic Energy Agency (IAEA-NSDD).

In the case of nuclear reaction data, the process is markedly different. The data from EXFOR is used to guide a physics-based model calculation through a variety of variance minimization procedures. This calculation is then compared to a set of “integral benchmark” data that are dependent on many different types of data including cross sections and emitted particle spectra, but are also extremely precisely known. The canonical example of such a benchmark is a critical assembly, where the ratio of neutron production to neuron loss (*k­eff*) is known to several significant figures. The resulting benchmarked data are then incorporated in the Evaluated Nuclear Data File (ENDF) [END] as well as several similar datafiles maintained by the international community. The vast majority of the effort put into the production of ENDF is provided by applications-oriented users due to its importance to national security, international counter-proliferation and nuclear energy. A significant consequence of this application focus is that the vast majority of the data in ENDF concerns neutron-induced reactions at either thermal (25 meV), fast fission or 14.1 MeV energies. This has profound implications for isotope production since the majority of the nuclides of interest to this community involve either charged-particle or broad-spectrum neutron-induced reactions, which are often overlooked during the reaction evaluation process.

Figure 1: The Nuclear data pipeline.

While ENSDF and ENDF contain a vast quantity of nuclear data, there are significant amounts of nuclear data that are either not contained in them because they “fall between the cracks” of nuclear structure and nuclear reactions, or they are present in a format that is not well-suited to their use in applications. Examples of this include the Atlas of Neutron Resonances [Mug06] which contains neutron capture resonance widths, centroids and cross sections. the Evaluated Gamma Activation File of (EGAF) capture gamma-rays [Fir15], and the Atlas of Inelastic Scattering of Reactor Fast Neutrons [Hur18]. Another very important nuclear data resource for applications is the Reference Input Parameter Library (RIPL) [Cap09] which contains both discrete (distilled from ENSDF) and continuous (Nuclear Level Densities and gamma-strength function) nuclear structure data needed for accurate reaction modeling.

The last step in the process involves *processing* the data into a form suitable for use in a particular application. Processing is also needed for the validation of nuclear reaction data using the integral benchmarks described above. Another role of processing is in the creation of application-specific databases, such as the Medical Internal Radiation Dose (MIRD) [MIRD] database used to guide medical treatment and diagnosis.

There are multiple ways to interact with the nuclear data evaluation process along the way, including through web interfaces hosted by the National Nuclear Data Center [NNDC] and the IAEA Nuclear Data Section [IAEA-NDS], a smartphone-based application [IAEA-APP] and publication in peer-reviewed journals including Nuclear Data Sheets [NDS] and Atomic Data and Nuclear Data Tables [ATNDT]. Figure 1 shows the “Nuclear Data Pipeline” that shows the flow of information from measurement through compilation, evaluation and processing, together with the ways in which external users utilize the underlying data.

Many different government agencies support nuclear data evaluation activities, including several components of the Department of Energy National Nuclear Security Agency (DOE-NNSA) and the National Criticality Safety Program (NCSP). However, the primary domestic organization responsible for organizing the evaluation process is the US Nuclear Data Program (USNDP) in the DOE Nuclear Physics office (DOE-NP). The USNDP is headquartered at the National Nuclear Data Center at Brookhaven National Lab and includes centers at Argonne, Oak Ridge, Los Alamos and Lawrence Livermore National Labs and joint lab/university programs at North Carolina State University/Triangle University Nuclear Lab, Michigan State University/National Superconducting Cyclotron Lab and the University of California/Lawrence Berkeley National Laboratory.

## International Collaboration

Much of the work of nuclear data evaluation takes place as a part of international collaborations covered under the Organization of Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA). The Nuclear Energy Agency (NEA) of the OECD covers the nuclear interests of its 33 member states.  For nuclear data, the Working Party on Evaluation Coordination is a collaborative effort between the nuclear data library projects from the NEA countries, ENDF/B (US), JENDL (Japan), JEFF (NEA), TENDL (Europe), BROND (Russia) as well as the non-OECD file project CENDL (China).

A powerful instrument of WPEC to accomplish progress in nuclear data is the so-called Subgroup (SG): members of WPEC identify a common area in nuclear data that requires improvement, and if enough support from the various data library projects is present, a Subgroup is defined that aims to move the field forward in a 3-5 year time frame. Recent successful examples of WPEC subgroups, which specific relevance to the US, are large-scale horizontal efforts like CIELO (SG40), on worldwide nuclear data evaluation for the most important fission energy related materials. The CIELO initiative has for example led to new ENDF/B-VIII evaluations for 235,238U, 56Fe and 16O among others, and the Generalized Nuclear Data (GND) format (SG38), or more specific efforts like covariance adjustment for improvement of nuclear data files (SG39).

WPEC also hosts long-term Expert Groups;current groups are working on the development of the  GND format, to provide a data library interface between nuclear physics and applications that are more modern that the ENDF-6 format, and the High-Priority Request List, which assembles the most important nuclear data requests from applications in a unified format, to stimulate experimentalists and evaluators to provide these data. A full list of past and current subgroups of WPEC is available at Ref. \cite{wpec}.

The International Atomic Energy Agency (IAEA) covers the interests of its 170 member states. The main task of the IAEA Nuclear Data Section is to provide fundamental nuclear databases for basic and applied use, with data originating from experiments and theoretical simulations,covering both nuclear structure and nuclear reaction data. An important collaboration coordinated by the IAEA is the Nuclear Reaction Data Center Network, which is responsible for keeping the EXFOR database of experimental nuclear reaction data up to date. The NNDC is responsible for the US input to the database.

In addition, the IAEA organizes Coordinated Research Projects (CRP) and technical meetings as instruments to align international nuclear data efforts towards the production of validated databases ready for applied use.  Examples of recent and current CRP's include a completed 2018 venture centered on nuclear data for primary radiation damage, an ongoing effort to improve nuclear model parameters for fission reaction calculations by modern nuclear modeling codes (such as EMPIRE, CCONE, COH3 and TALYS), and an effort to create a first-ever evaluated database of radiative strength. In 2019, a CRP on fission yields will start which aims to produce updated fission yield libraries for the major actinides, in response to requests from reactor technology, safeguards and non-proliferation.

Nuclear data evaluations of neutron-induced reactions for fission applications are covered by the International Nuclear Data Evaluation Network (INDEN), an IAEA initiative which continues the CIELO efforts of the NEA for differential nuclear data development, and evaluations, for the most important materials relevant to fission technology. Other long-term projects are the nuclear structure and decay data network (NSDD), nuclear data for medical isotope production (with emphasis on data needs for monitor reactions and accelerator), neutron standards, and the Fusion Evaluated Nuclear Data Library (FENDL).

# Crosscutting nuclear data needs

While nuclear security, energy and isotope production each have unique nuclear data needs, there are certain items that are common to all of them. One these involves neutron-induced reactions and their outputs on the “Big 3” actinides (235,238U and 239Pu) which produce energy in nuclear reactors and weapons and to produce certain high-value radionuclides for medical and research applications. While there has been a significant focus on (n,f) reactions on the “Big 3”, inelastic neutron scattering has tended to “take a back seat” due to its lack of a clear signature which had led to a deficit of high-quality experimental data. Another crosscutting need is for good information regarding highly-excited continuum states, particularly for nuclei on or near the valley of stability which is needed for accurate reaction modeling.

In this section we explore all three of these cross-cutting needs together with the paradigmatic example of the interpretation of the reactor anti-neutrino signal.

## Fission on the “Big-3” Actinides – 235,238U and 239Pu

Walid puts his input here.

## Improved 235,238U and 239Pu(n,n’) data for neutron transport

A robust neutron transport capability for fast neutrons is an essential element for accurately modeling nuclear reactors and national security applications. However, improvements in neutron scattering data have hampered by the fact that these reactions do not lead to the production of an easily measured signal like fission, or a radiochemical observable like neutron capture. The result has been significant disagreements between different reaction evaluations. These disagreements manifest themselves as *compensating errors* that are resistant to the validation process. This issue has been recognized by the nuclear data community since the early days of the WPEC [Row89] and more recently by Maslov [Mas11].

One compelling example of this is the work of *Bauge* [Bau12] for the case of the Jezebel 239Pu critical assembly.Models of Jezebel using data from both the BRC09 and ENDF/B-VII databases reproduce a unity value of *keff* to better than 1 part in 104. However, when the authors substituted one nuclear quantity from the ENDF/B-VII database with a corresponding value from BRC09, the value of *keff* varied considerably. The greatest changes came from “swapping out” the elastic and inelastic scattering cross sections, which led to changes in the *keff* of +522 pcm and -638 pcm respectively. This is shown in Fig. 2 to the right.



Figure 2: Variations of the JEZEBEL reactivity induced by the different components of the evaluated BRC09 and ENDF/B-VII.0 239Pu file from *Bauge*.

Elastic and inelastic scattering on all three major actinides are poorly constrained. This deficiency was recognized by the international nuclear data community, and a new Collaborative International Evaluated Library Organization (CIELO) Coordinated Research Program was started under the auspices of the IAEA [Cha14]. The purpose of CIELO was to have the entire international nuclear data evaluation community agree on a set of evaluated cross sections and output spectra for six critically-important nuclei: 1H, 16O, 56Fe, 235,238U and 239Pu. Recently, this list has been expanded to include 14,15N, 9Be, 23Na, 59Co, 58Ni, 238-242Pu.

CIELO has relatively little energy or angle differential data to draw upon to aid in its evaluation of (n,n’) on the “Big 3” Actinide, leading to *“significant differences amongst the evaluations for 239Pu in the fast energy range, with ENDF/B-VII.1 and JENDL-4.0 lying significantly above the JEFF-3.1 evaluation.”* [Cha14]. The 239Pudata referenced in their paper are all from indirect measurements made prior to 1970 [Bat69, And61]. The case is similar for 235U where they note that differences for *En* > 50 keV *“have a large impact on the fast criticality (Godiva), leading to a 540 pcm swing in calculated criticality, as shown by Go Chiba [Chi12].”*

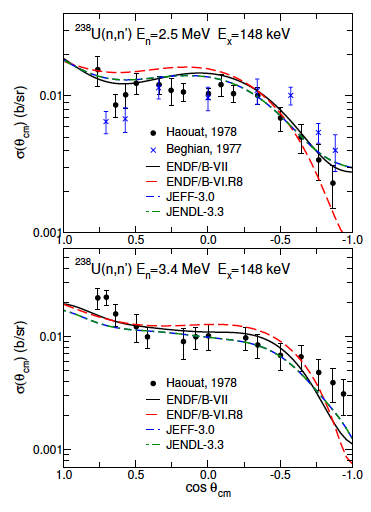


Figure 3: Angle-differential cross section data and evaluations for the 238U(n,n’) reaction leading to the population of the 2nd excited state at 148 keV for 2.5 and 3.4 MeV incident neutron energies from [You07].

While a significant amount of energy-differential data evaluation 238U, including data for the (n,f) [Beh76,Fro88,Poe81], (n,) below 2 MeV [Bul88,Voi86,Ada88], (n,2n) [Fre80a,Fre80b,Kon93] and even the (n,3n) [Vee78,Fre80a] reaction channels, there are only two high-uncertainty (≈20-40%) measurements of the angle-differential (n,n’) cross section by *Haouat* [Hau82] and *Beghian* [Beg79]. The combination of an abundance of high-precision data for (n,), (n,f) and (n,2n) channels, together with a paucity of such information for (n,n’), has led to striking disagreements between the various evaluations, particularly as a function of outgoing neutron angle. This is clearly seen at forward and backward angles in Fig. 3. There are also significant disagreements between angle-integrated, energy-differential (n,n’) cross section measurements and evaluations leading to the population of the first few states in 238U [Gue75,Lit90] over the entire energy range of interest for fission-based applications.

One significant source of (n,xn) partial cross section data from 1997 to 2003 was the GEANIE collaboration (Germanium Array for Neutron-Induced Excitations) at the Los Alamos Neutron Science Center/Weapons Neutron Research (LANSCE/WNR) facility. While the primary goal of the GEANIE collaboration was the determination of the 239Pu(n,2n) cross section [Ber02], it resulted in the publication of more than two dozen papers over the course of more than 15 years. Experiments were run on all three of the major Actinides: 235U [You02], 239Pu [Ber02] and 238U [Fot04].

GEANIE produced the first high-resolution partial -ray cross section data on the Big-3. Figure 4 show the two strongest partial 239Pu(n,n’) cross sections measured at GEANIE together with calculations using the CoH reaction modeling code developed by Toshihiko Kawano. It should be noted that the GEANIE data was angle-integrated with respect to the outgoing neutron, limiting its value for neutron transport modeling.



Figure 4: A selection of the 238U(n,n’) partial -ray cross sections from [Fot04] for the two lowest members of the ground state band and the first 1- level.

GEANIE did not include any neutron detectors, meaning that only angle-integrated partial -ray cross sections were measured. The need for new data has motivated the international and domestic community to perform new experiments. This has included energy-differential/angle-integrated measurements of the 238U(n,n’) cross section using the GELINA spallation neutron source in Geel Belgium by *Bacquias et al.,* [Nem13] and quasi-angle-differential measurements using the Rensselaer Polytechnic Institute Linac by *Daskalakis et al.,* [Das14]. Furthermore, measurements of the 238U(n,n’)cross sections as a function of both outgoing neutron angle and energy have also been called for in the NEA High Priority Reactions List (<http://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=435)>.

The ideal way to improve (n,n’) data on the 235,238U and 239Pu would be to perform measurements of the scattered neutron in coincidence with the gamma-ray emitted by the excited nucleus. Unfortunately, neutron beams usually have quite low intensity, with a fluence in the fast (1-10 MeV) region between 103 and 107 n/s/cm2 at the target location. Furthermore, many spallation neutron sources have a significant high energy spectral component that can cause inter-element scattering in a neutron scintillator array rendering precise determination of the scattered neutron energy hard-to-impossible to perform. However, intense limited-energy neutron sources based on thick-target deuteron breakup [Har18] and forward-fitting techniques developed for use at spallation neutron sources [Kee18] off an opportunity to perform neutron-gamma coincident measurements in the fast fission energy spectrum. These techniques could provide valuable data to improve nuclear data evaluations of inelastic scattering, even on targets where fission is an open channel.

## Improved treatment of continuum nuclear data properties

Information regarding the structure of states in the unresolved continuum region above the particle separation energy is of central importance to accurately modeling the competition between particle and gamma-ray emission. One of the most important of continuum properties is the nuclear level density (NLD) as a function of energy, spin and parity since the relative production of different exit channels. The radiative strength function (RSF), which describes the ability of excited nuclear matter to absorb or emit photons, also plays a major role in determining the competition between neutron capture and emission for compound nuclei near the neutron separation energy (typically 4-8 MeV).

A number of recent studies has shown the importance of the RSF to modeling (n,) reactions for neutrons with energies between 1 and 100 keV, which corresponds to not only the temperature at which rapid neutron capture nucleosynthesis occurs in stars [Lar10, Lar15], but also to the majority of neutrons in a number of molten salt reactor designs. Furthermore, recent work led by the group at the University of Oslo has shown that there is a surprisingly large amount of M1 radiative strength believed to be a type of “scissors” collective mode throughout the Actinide mass region near the valley of stability including 238U, 239,240,242Pu and 232Th [Lap16, Gut13, Gut13a, Gut14, Gut15]

These Actinide studies show that the NLD appears to follow a constant temperature (CT) form:

(1)

where *E­x* is the excitation energy, and *T* and *E0* are adjusted to reproduce the behavior of the low-lying discrete states. The level density is also modeled as having a roughly Gaussian dependence on angular momentum:

(2)

with an energy-dependent width spin cut-off parameter (**) of the form:

(3)

where *U* is roughly the *Ex* minus the pairing gap **, *a* is the level density parameter, *A* is the nuclear mass and is the asymptotic level density value one would obtain in the absence of any shell effects. This

There is a great deal uncertainty in the magnitude of the spin cut-off parameter. This is a significant issue since a good knowledge of the *J* distribution is needed to accurately model the neutron vs. -ray emission probability in nuclear reactions. This sensitivity was shown recently by Wiedeking *et al.,* [Wie16] who showed that neutron emission from excited states in 95Mo well-above the neutron separation energy populated via (d,p) was hindered for states with high angular momentum. Uncertainties in the spin cut-off parameter could potentially have a dramatic influence on neutron capture cross sections at *keV* energies in weapons systems, astrophysical nucleosynthesis and fast reactor design.

Figure 5: Ratio of the 238U(n,n’) cross section to the state calculated using TALYS for two different sets of input parameters as a function of incident neutron energy. The solid line shows the ratio where spin cutoff has been scaled to ±25% of its default value. The dashed line shows the case where the default value calculated using LD Model 1 (Gilbert and Cameron) is divided by the value obtained using the data from *Guttormsen* [Gut13a].

=0.75/=1.25

(n,n’) provides a useful tool for studying the spin cut-off parameter since the reactions proceed largely through the population of a compound nucleus with a relatively wide range of angular momentum. As the energy of the incident neutron increases, a wider range of states can be populated *if they exist.* The dependence on spin cut-off would be most evident in the energy dependence of the (n,n’) partial cross section to off-yrast states. Reaction modeling bears this out. Figure 5 shows the ratio of the partial cross section for the population of the level in 238U(n,n’) as a function of incident neutron energy calculated using the TALYS reaction code for two different choices of spin cut-off. The solid line shows the case where a constant temperature level density is assumed and the spin cut-off parameter was varied from 75% to 125% of its “normal” value given by the equation (3) above. The ratio decreases by nearly a factor of 2 with increasing energy. In contrast, the dashed line shows the ratio of the population of the state when the LD and RSF (from recent Oslo measurements [Gut13a]) is divided by the results obtained using the default Gilbert and Cameron in TALYS. In this case the ratio decreases by nearly a factor of 2. Similar behavior is seen in the partial cross sections for other off-yrast levels as well.

Information regarding the spin cutoff parameter can also be obtained through observation of the relative population of two low-lying states with very different spins via activation. This method has been used in Hg and Au by Chakravarty [Cha92] and more recently by Sudar in Hg and Pt [Sud06]. Figure 6 shows this for the case of the 52mMn(Jπ=2+)/52gMn(Jπ=6+) ratio populated via 56Fe(p,n) measured via stacked target activation at the LBNL 88-Inch cyclotron as compared to TALYS calculations for different values of the spin cut-off parameter.

It should be noted that both the (n,n’) and isomer-to-ground state ratio measurements could be performed as part of a program that supports improved neutron transport as described in Section II.B above, and a program of cross section measurements in support of medical isotope production described in sections IV below. This reflects the interdependency between nuclear data over a wide range of applications.



Figure 6: Predictions of the production of 52mMn (2+)/52gMn(6+) isomer-to-ground state ratio as a function of energy for the Gilbert and Cameron level density (left) and using the 6 level density models available in TALYS (right).

# National Security and Non-proliferation

*Something general from Cathy goes here.*

## Interpreting the reactor anti-neutrino spectrum

One canonical example of a non-proliferation activity where improvements in multiple cross-cutting areas of nuclear data are needed is the interpretation of the anti-neutrino spectrum from the prompt decay of fission fragments in the core of a nuclear reactor. Nuclear reactors are prolific sources of electron antineutrinos, producing about 1021 antineutrinos per second for a typical power reactor. These electron antineutrinos are produced by the beta-minus decay of the more than 800 neutron-rich fission fragments, which are the debris from the main source of energy generation in a reactor, the neutron induced fission of actinide nuclides. These antineutrinos are also the only radiation escaping from the vessel of a safely operating nuclear reactor, making them ideally suited for reactor monitoring, even in the event that the actor operating the reactor refuses to cooperate with the international community. Recent technological advancements in electron antineutrino detection has made another dream a reality, monitoring the performance of nuclear reactors and tracking 239Pu for non-proliferation treaty verification. The WATCHMAN experiment in the UK has just started to explore this field [Cha18]. Furthermore, the possible use of antineutrino detectors for the detection of nuclear explosions has been discussed [CarAx].

Nuclear reactors have also been an essential tool to study the weak interaction. Their large antineutrino flux was capitalized by Cowan and Reines to discover antineutrinos in 1956 [Cow56], more than 25 years after they were first hypothesized by Pauli in 1930 to explain the continuum electron spectra observed following beta-minus decay. In the last few years, the transformation of electron antineutrinos into the other two flavors was beautifully measured by three large-scale experimental efforts, Daya Bay [An16], Double Chooz [Abe12] and RENO [Cho16]. These experiments also confirmed a deficit of antineutrinos of about 5-9% at short distances that had been revealed in a 2011 re-analysis of the conversion procedure to obtain antineutrino spectra from the measured electron spectra [Men11].

This intriguing deficit, as well as a spectrum distortion, has triggered a new generation of very-short distance reactor experiments, such as NEOS (Korea) [Ko17], DANSS (Russia) [AleAx], STEREO (France) [AllAx], PROSPECT (USA) [Ash16], and SoLid (Belgium) [Kal17], whose first results are beginning to be made public. There are no signs of slowing down in the field of nuclear reactor antineutrinos, as the largest experiment to date, JUNO designed to measure the neutrino mass hierarchy should be ready for data taking by 2021 [SalAx]. JUNO will feature a 20 Million-Ton detector at 80 km from A 27 GW nuclear power plant in China.

The antineutrino spectrum produced in a nuclear reactor is calculated as the sum of the spectra produced by each of the nuclear fuels, 235,238U and 239,241Pu, weighted by the respective fission fractions [Vog81]. The spectra for each fuel can be calculated using nuclear databases, in what is commonly known as the ‘summation method’. Alternatively, for 235U and 239,241Pu the spectra can also be calculated by converting the aggregate electron spectra measured at ILL in the 1980s [Fel82,Sch85,Hah89]. The current best predictions for the 235U and 239,241Pu are those by Huber [Hub11] using the conversion method, while for 238U is that by Mueller *et al.* [Mue11] using a hybrid conversion-summation method.

The use of nuclear databases to calculate antineutrino spectra is considered less precise than the conversion method due to deficiencies in the underlying fission and decay data, such as beta intensities [20], beta shape factors due to first-forbidden transitions [Hay14], evaluated libraries issues [Son15] and fission yields [Son16]. There have been considerable efforts in the last few years to improve this situation, including: (i) experimental campaigns in Jyvaskyla [Alg10], ORNL [Ras16] and ANL [MccTBD] to obtain highly precise values of beta intensities, which have been incorporated in the ENDF/B-VIII.0 decay data sub-library; (ii) measurements of isomeric ratios in ILL, Jyvaskyla and ANL; (iii) measurements of fission yields in GELINA [Viv00], GSI [Pel17] and LANL [Duk16]; (iv) a recent IAEA Coordinated Research Project on beta-delayed neutron emitters [DimXX] that would improve the derivation of cumulative fission yields from independent ones. Also planned are measurements of beta shape factors as well as a new IAEA Coordinated Research Project to evaluate fission yields.

Another issue affecting the summation method is the lack of fission yield correlation matrices in the evaluated fission data libraries. As a result, uncertainties cannot be fully computed. There has been some progress in this area, for instance, the ongoing OECD-NEA subgroup 44 will incorporate this topic [SobXX].

The summation method has been recently applied in two different situations. First, it has been shown that the Daya Bay fuel evolution data [An17] can be explained by summation calculations including an anomaly of about 4% [Hay18]. Second, a novel method to analyze the Daya Bay spectrum revealed the signature of 4 individual fission products, while the same method applied to the electron spectra revealed two additional fission products [Son18].

The conversion method is not fully free of issues, either. To start, it is based on a single set of measurements; also, its most basic premise, the description of a level to level spectrum using a particular formalism has not been tested as highly precise measurements of electron spectra for fission products above the inverse beta decay cross section threshold have not been published. As a result, while more precise than the summation method, it is nevertheless considerably less reliable. A recent article [Son17] reviewed the different Fermi functions available for the calculation of spectra and showed that a linear correction factor of 6%/MeV could explain the anomaly.

Given the dependence of the antineutrino signal on both decay and fission product yield data a series of sensitivity study-guided integral experiments, along the lines of critical assembly integral benchmarks, to validate the underlying nuclear data would provide a strong constraint on the underlying data. One approach would involve irradiating fissile and fissionable samples in facilities with well-understood neutron spectra and comparing the observed delayed gamma-rays to a modeled spectrum produced using the Fission Induced Electromagnetic Response (FIER) code developed at Berkeley [Mat18]. FIER convolves fission product yield distributions and decay data to predict the gamma-ray spectrum after neutron irradiation. The first example of its use involving a comparison to the delayed gamma-ray spectrum from a 235U foil irradiated in the Godiva critical assembly indicated several cases were the underlying fission yields or decay data required improvement. One example, where the yield of the 132I needed to be adjusted upward by 1.5s is shown in Figure 7.



Figure 7: Difference in the FIER-predicted and observed yield of 132I as a function of time for a 235U sample irradiated at the GODIVA critical assembly taken from [Mat18].

These experiments would involve a sample of depleted 238U since recent results from IBD indicate that the contribution to the observed anomaly in the antineutrino experiment can be attributed to issues with the 238U(n,f) yields. These measurements could be performed at the Godiva in the same fashion as the 235U irradiation used to validate FIER, or other well-documented fast neutron facilities including the thick target deuteron break neutron source at the LBNL 88-Inch cyclotron [Har18] and the High Flux Neutron Generator at UC-Berkeley [All18] and compare the results to the FIER predictions to inform both the fission yield and decay data for 238U(n,f).

## Improved (n,x) data for active interrogation

An invaluable tool for determining the presence of fissile materials for non-proliferation involves prompt neutron- and gamma-ray spectroscopy coupled to a DT neutron sources with associated particle imaging (DT-API). DT-API sources allow tracking of the trajectory of individual neutrons, thereby greatly decreasing background from scattered neutrons. The signal from DT-API generators includes long-chain gamma-ray emission from multiple fission events [Pra12,Nak10] as well as prompt gamma- and neutron scattering on a wide range of low- and high-Z materials.

The interpretation of this data requires detailed knowledge of both the double-differential neutron scattering and gamma-ray production cross sections from fast down to thermal neutron energies. The Evaluated Gamma Activation File [Fir14] provides partial gamma-ray cross section data for transitions between discrete states following thermal neutron capture. At higher energies the Atlas of Gamma-rays from the Scattering of Reactor Fast Neutrons [Dem78] which has recently been compiled into a database and reconciled to reflect state-of-the-art gamma-ray energies from ENSDF [Hur18] offers discrete gamma-ray cross sections for irradiation with fast fission neutrons.

A program of measurements of gammas emitted from both discrete and QC states would require a relatively modest effort to set in place. The data from these measurements could then be used to guide physics-based reaction model, such as the COH, TALYS or EMPIRE to ensure that the total gamma-ray production cross section is consistent with the total capture and scattering cross sections themselves.

# Isotope Production

The high energy density and wide range of decay lifetimes and chemical properties of radionuclides near the nuclear valley of stability make them an extremely versatile tool for applications ranging from the diagnosis and treatment of illness, to nuclear non-proliferation and environmental studies, to powering spacecraft to explore the outer reaches of the solar system and beyond. Furthermore, given that there are hundreds of unstable nuclei with lifetimes in excess of 1 hour and less than 100 years between Hydrogen and Californium, it is clear that we have barely scratched the surface of potential applications.

However, there are significant uncertainties in both the reactions used to produce these radionuclides and/or the intensities and energies of their decay radiation. There have been numerous papers produced over the past 5 years detailing some of the nuclear data needs associated with producing radionuclides for applications. For a comprehensive listing of nuclear data needs associated with radionuclides we refer the reader to the summary whitepaper from the Nuclear Data Needs and Capabilities for Applications Workshop held in Berkeley in 2015 [Ndn15], particularly the reactions and isotopes listed in Appendix B. Additional guidance regarding nuclear data needs for medical isotopes can be found in a recent series of IAEA studies [Iae675,Iae596,Iae591] as well as an exhaustive paper from Qaim *et al.* [Qai17].

In this section we will focus on nuclear data needs associated with the production of radionuclides for medical imaging and therapeutic applications, due to its dominant role in society. Over 20 million nuclear medicine procedures are performed each year in the United States [Met09]. 99mTc (t½= 6.0067(5) hour), which decays predominately via the emission of a single 140 keV gamma-ray, is perhaps the most well-known medical radionuclide, and is used in 80% of medical imaging procedures. The primary production route for this isotope is through -decay of a longer-lived 99Mo (t½= 65.976(24) hour) “generator” via 235U(n,f). However, this route is less than ideal due to the increasing age of many reactors [Qai12] and a proliferation risk associated with reactors utilizing Highly-Enriched Uranium (HEU). As a result, alternative 99mTc production pathways, as well as studies of the associated production of long-lived impurities [Upd13], are under consideration [Rut09].

Another commonly-used imaging radionuclide is 18F (t½= 109.771(20) min), which is used in Positron Emission Tomography (PET). 18F PET imaging is now so commonplace that there are numerous companies providing production capabilities built around low-energy “medical cyclotrons” designed to produce 18F via the 18O(p,n) reaction. The utility of PET imaging, combined with the recent rise in multimodal PET/MRI and PET/CT imaging, has led to significant interest in the development of other + emitting radionuclides. Two recent examples include 82Rb (t½=1.2575(2) min) which is used in cardiac imaging, and 68Ga (t½=67.71(8) min), used in the detection of a wide range of tumors. The short half-lives of 82Rb and 68Ga necessitate that they be extracted from a longer-lived radioactive parent generator. The 82Sr/82Rb and 68Ge/68Ga radiochemical generators, which have parent half-lives of 25.35(3) and 270.93(13) days, respectively, allow them to be produced at regional facilities and distributed to medical facilities throughout the world.

In addition to imaging, a large number of therapeutic radiopharmaceuticals are under development for cancer treatment. The principle behind radionuclide cancer therapy involves depositing a **targeted** dose, e.g., energy per unit mass, to a tumor cell, capable of producing damage to multiple strands of DNA, from which the cell cannot recover. The ideal dose delivery involves radiation with a high Linear Energy Transfer (LET). While some - nuclides are already in use, such as 177Lu (t½= 6.6475(20) days), the relatively long range of -particles makes them less favorable than other modes of radioactive decay. These include Auger/Coster-Kronig electron-emitters, which typically have a range of less than 1 µm, or -particle emitters, which have ranges of 2-10 µm.

There is a particularly large amount of interest in the alpha-emitting radionuclide 225Ac. 225Ac is particularly well-suited for therapeutic applications in that it has a sufficiently long lifetime (t½= 10.0(1) days) to facilitate its incorporation into targeting biomolecules, and its daughters subquently decay relatively rapidly (t1/2<3.2 hours) to stable products, thereby minimizing concurrent dose to healthy tissue. Other promising alpha-therapeutic radionuclides include 211At, 212Pb/212Bi, 213Bi, 226Th and 227Th and have all been identified as high priority topics by the most recent Nuclear Science Advisory Committee’s Long Range Plan on Isotope Production [Nsa15].

A particularly promising nuclear medical treatment modality involves coupling a pair of radioisotopes, including a therapeutic nuclide capable of delivering a highly localized radiation dose and a chemically-similar isotope that emits a positron for PET or a gamma suitable for single photon emission computed tomography (SPECT) imaging. Examples of these “theranostic pairs” include 188Pt or 191Pt for use in imaging, together with 193mPt, 195mPt and 197Pt, which all have therapeutic potential. Another promising pair involves the PET isotope 134Ce (t½= 3.16(4) days) combined with 225Ac. A recent NSAC report [Nsa15] highlights additional pairs of isotopes that have potential uses as theranostic agents.

As mentioned above, most of these promising radionuclides are made at a few regional facilities. These include the Isotope Production Facility at Los Alamos National Lab (IPF-LANL) and the Brookhaven Linac Isotope Production facility at Brookhaven National Lab (BLIP-BNL) in the United States, TRIUMF in Canada, and iThemba LABS in South Africa. These facilities produce all types of medical isotopes, ranging from non-standard + emitters to SPECT radionuclides via generators, as well as numerous therapeutic isotopes [Iae675,Nsa15]. In a compelling example of the synergy between fundamental nuclear research and societal benefit, LANL-IPF and BLIP-BNL operate symbiotically with the Los Alamos Neutron Science Center at LANL and the Relativistic Heavy Ion Collider at BNL. This dual-use approach provides an inexpensive, reliable source of radionuclides needed for the development of new drugs through a public-private partnership.

These facilities utilize high-energy (≥100 MeV) proton beams for isotope production via (p,x) reactions on stable targets. Nuclear reactions in this energy region range from pre-equilibrium direct/deep inelastic mechanisms to the formation of fully equilibrated compound nuclei. These reactions produce many “secondary” spallation protons and neutrons that can in turn initiate nuclear reactions, providing either a useful alternative source of valuable radionuclides or a troublesome chemically-identical contaminant. The secondary neutron flux is particularly important since the lack of electronic stopping for neutrons makes them advantageous for radionuclide production [Voy18a]. The energy spectrum of secondary neutrons from IPF was recently measured using spectral unfolding [Mos16] and for thick-target deuteron break-up on beryllium at the LBNL 88-Inch cyclotron via a secondary time-of-flight technique [Har18]. A number of therapeutic radionuclides can potentially be produced via secondary neutron-induced (n,p) reactions. Examples of possible targets include 32S, 47Ti, natZn (for the production of 64.67Cu), 105Pd, 149Sm, 175Lu, and 177Hf. In addition, the production of alpha-emitting radionuclides such as 225Ac, 223Ra, and 227Th using neutrons has yet to be explored. Finally, 99Mo could be produced using spallation neutrons to induce fission in 232Th or 238U.

Unfortunately, the transition between compound and pre-compound reaction mechanisms, together with the large number of open channels at these energies, makes accurate modeling of both proton- and neutron-induced reactions on both light and heavy nuclei in this energy region notoriously difficult. Figure 8 shows a comparison between cross sections for the production of 32Si and 225Ac from (n,x) reactions on 36S and 232Th,calculated with the reaction codes typically used to model isotope production. This includes EMPIRE-3.2.3 [cite-empire], CoH [cite-coh] 3.5.1, ALICE-2017 [cite-alice], the TENDL-2011 and TENDL-2017 libraries produced using TALYS [cite-tendl], as well as the most recent version of the code (TALYS 1.9) [cite-talys] and the European Activation File (EAF-2010).



Figure 8: Predictions of several major reaction modeling codes for the (n,x) reactions leading to the production of 32Si and 225Ac. Differences of up to an order of magnitude are commonly seen.

The large uncertainties in reaction modeling at these energies means that direct measurement of the reaction cross sections themselves is necessary in order to design targets capable of efficiently producing the radionuclides of interest. Fortunately, and in contrast to the astrophysical case, most of the reactions of interest for radionuclide production take place on stable targets and are therefore experimentally accessible.

The preferred method for measuring cross sections involves foil activation, in which one or more well-characterized thin foil(s) are irradiated at a single beam energy and a well-measured current, and the residual radioactivities are quantified through off-line alpha, beta, gamma, or electron spectroscopy [Gra16, Voy18b]. In this case the reaction cross section can be deduced from the number of residual nuclei formed via the equation:

(4)

In this approach, the uncertainty in the deduced cross section depends strongly on the accurate characterization of the composition, density () and thickness () of the target material, precise measurements of the incident particle flux (), and the spectroscopic assaying techniques used. Access to well-characterized nuclear data can be useful in reducing the latter two sources of uncertainty. In many experiments, targets are difficult-to-impossible to form due to their physical or chemical properties, introducing large systematic uncertainties into activation foil measurements.

The incident particle flux (), is commonly measured using a well-characterized monitor reaction leading to the production of an easily quantified residual nucleus. For charged-particle induced reactions, relatively few monitor reactions in the low-to-intermediate energy regimes of 30-70 MeV have been accurately measured (*i.e*. to a few percent level). Above 70 MeV, monitor reactions whose experimental measurement is free from the influence of secondary neutron contributions to residual yields are not well characterized. Knowledge of these cross sections as a function of the incident particle energy is central to the isotope production effort. Recent efforts have focused on developing 93Nb(p,4n)90Mo (t½= 5.56(9) hours) as a monitor reaction suitable for use at regional isotope production facilities [Voy18b, Kim18].

# Nuclear Energy

This is where Brad can insert his section

# Future directions in nuclear data

## Training the next generation of evaluators

The penultimate part of the paper will discuss the need to train the next generation of nuclear scientists and engineers capable of addressing these needs. This will include a recognition of the increasing role that machine learning will play in the nuclear data modeling and evaluation process, and the possibilities offered by the new generation of high-resolution gamma-ray and particle spectrometers and accelerator facilities.

## The Nuclear Data Interagency Working Group – A new path forward

In recent years there has been a growing recognition of the need to develop a plan that addresses nuclear data needs from measurement through, compilation and evaluation in an organized, multi-agency fashion. This process started in July 2014 with the first review of the US Nuclear Data Program, which is administered through the Nuclear Physics office in the US Department of Energy (DOE-NP), in nearly two decades. The review led to DOE-NP requesting that a Nuclear Data Needs and Capabilities for Applications Workshop (NDNCA) be organized to compile a listing of nuclear data needed for nuclear energy, national security and isotope production. NDNCA was held in Berkeley in May 2015 [] and a whitepaper delineating these needs was released 5 months later.

Following NDNCA, Dr. Catherine Romano, working with the DOE-NP and the NNSA office on counter-proliferation research and development (NA-22), organized a grassroots “Nuclear Data Working Group” (NDWG) comprised of subject matter experts selected by the program managers who support their activities to identify a “roadmap” to address the most important and crosscutting nuclear data needs including all steps in the nuclear data pipeline from measurement through compilation, evaluation and processing. The NDWG presented their results to program managers from DOE-NP, DOE-Nuclear Energy, the Isotopes Program, the Defense Threat Reduction Agency, the Department of Homeland Security and the several offices within the National Nuclear Security Administration in April 2016. The component of the roadmap concerning nuclear data needs for non-proliferation was further refined at a Nuclear Data Roadmapping Enhancement Workshop (NDREW) held in Washington DC in January 2018.

In response to the plan presented by the NDWG, the program managers formed their own Nuclear Data Inter-Agency Working Group (NDIAWG) to pursue a collaborative effort to address several of these high-profile nuclear data needs in a collaborative fashion.

The NDIAWG issued two Funding Opportunity Announcements in 2017 and 2018 that led to a total of 11 covering topics from improving fission fragment yield and gamma-ray decay data to measuring specific high-priority cross sections for isotope production and neutron transport for nuclear reactors.

A key element of the NDIAWG process is ensuring that the efforts to address these nuclear data needs follow the established roadmap by reviewing the progress made via recurring interagency workshops. The first of these was the Nuclear Data Roadmapping Enhancement Workshop (NDREW) held in Washington DC in January 2018, which focused on nuclear data needs relevant to non-proliferation [Ndr18]. The second of these, a Workshop on Applied Nuclear Data Activities (WANDA) is planned for a year-later in Washington DC as well.

The NDIAWG process reflects a growing recognition that improved nuclear data are essential to a wide range of human endeavors that transcend the needs of any one societal need or governmental mission. Its goal is the development of a new, multi-agency *national* plan to address nuclear data needs in a coherent way. This plan, which is being developed in partnership with international collaborators at the IAEA and the OECD-NEA represents a new paradigm for collaborative research.