ORNL/TM-2024/3462

Proceedings for the Workshop on Applied Nuclear Data Activities 2024

Jesse M. Brown[1]
Amy E. Lovell[2]
Robert Casperson[3]
Nathan Gibson[2]
Matthew Gott[1]
Laura Gustad[5]
Paul Humrickhouse[1]
Keegan Kelly[2]
Michael Loughlin[1]
Stephanie Lyons[4]
Khachatur Manukyan[6]
Ugur Mertyurek[1]
Denise Neudecker[2]
Ellen O'Brien[2]
Sofia Quaglioni[3]
Paul K. Romano[7]
Etienne Vermeulen[2]
Paul Wilson[8]
Todd Bredeweg[2]
Jennifer Jo Ressler[3]

[1]Oak Ridge National Laboratory
[2]Los Alamos National Laboratory
[3]Lawrence Livermore National Laboratory
[4]Pacific Northwest National Laboratory
[5]Missile Defense Agency
[6]University of Notre Dame
[7]Argonne National Laboratory
[8]University of Wisconsin–Madison

August 9, 2024

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2024/3462

PROCEEDINGS FOR THE WORKSHOP ON APPLIED NUCLEAR DATA ACTIVITIES 2024

Jesse M. Brown[1]
Amy E. Lovell[2]
Robert Casperson[3]
Nathan Gibson[2]
Matthew Gott[1]
Laura Gustad[5]
Paul Humrickhouse[1]
Keegan Kelly[2]
Michael Loughlin[1]
Stephanie Lyons[4]
Khachatur Manukyan[6]
Ugur Mertyurek[1]
Denise Neudecker[2]
Ellen O'Brien[2]
Sofia Quaglioni[3]
Paul K. Romano[7]
Etienne Vermeulen[2]
Paul Wilson[8]
Todd Bredeweg[2]
Jennifer Jo Ressler[3]

August 9, 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

DOE	US Department of Energy
DTRA	Defense Threat Reduction Agency
FES	Fusion Energy Sciences
FOA	funding opportunity announcement
FY	fiscal year
IP	Isotope R&D and Production
NCSP	Nuclear Criticality Safety Program
ND	nuclear data
NDEM	Nuclear Data Exchange Meeting
NDIAWG	Nuclear Data InterAgency Working Group
NDNCA	Nuclear Data Needs and Capabilities for Applications
NDWG	Nuclear Data Working Group
NNSA	National Nuclear Security Administration
NP	Nuclear Physics
NSAC	Nuclear Science Advisory Commitee
RAFM	reduced-activation ferritic-martensitic
TBR	tritium breeding ratio
UQ	Uncertainty Quantification
WANDA	Workshop for Applied Nuclear Data Activities

ACKNOWLEDGMENTS

The organizers would like to thank Lisa Felker and Stacy La Pineda for their exceptional effort in handling the meeting logistics both before and during the meeting. They would like to thank Cheryll Nunes for A/V support and ensuring that all of the presentations ran smoothly throughout the course of the week. They would additionally like to thank Peter Brain, Jeremias Garcia-Duarte, Erin Good, Joe Henderson, Jonathan Morrell, Aaron Tamashiro, and Noah Walton for their service as rapporteurs during the workshop.

Support for WANDA2024 was provided by the Nuclear Data InterAgency Working Group.

This work is supported by the US Department of Energy Office of Fusion Energy Sciences under award number DE-SC0022033. The work by staff from several laboratories was performed under the auspices of the US Department of Energy by Los Alamos National Laboratory under Contract 89233218CNA000001, Oak Ridge National Laboratory under Contract DE-AC05-00OR22725, Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, Pacific Northwest National Laboratory under Contract DE-AC05-76RL01830, and Argonne National Laboratory under contract DE-AC02-06CH11357.

ABSTRACT

The Workshop for Applied Nuclear Data Activities (WANDA) is designed to increase communication among nuclear data (ND) users in multidisciplinary federal programs, ND producers, ND funders, and other ND experts. It also presents an opportunity to cross-pollinate ideas as well as introduce ND gaps identified by federal programs to ND experts and ND capabilities to the various federal ND users. WANDA 2024 included five technical sessions, three of which focused on Fusion Energy Sciences (FES)—FES Fusion Neutronics, FES Tritium Production, and FES Material Damage—and two stand-alone sessions—Isotopes and Targetry for Nuclear Data and Uncertainty Quantification.

The FES sessions successfully brought new voices to the WANDA discussions, expanding the application space in which nuclear data are critical. FES programs need accurate nuclear data with realistic uncertainty quantification to properly estimate, for example, shielding, activation, tritium production, helium production, structural material integrity, and superconducting magnet operation. This includes a variety of projectile (neutrons, photons, charged particles) and target atoms. One of the action items common to all the FES sessions was a need to perform sensitivity studies to identify the prioritization of nuclear data needs.

The Isotopes and Targetry session highlighted the many capabilities available to produce high-quality targets for nuclear data measurements, including 3D printing with spherical powders, combustion synthesis coupled with spin coating & electrospraying, inkjet printing, and isotopic doping. These new methods open doors for more accurate measurement, but it was also stressed that sample characterization following any method of fabrication is of the highest importance to accurately interpret nuclear data measurement results that used that sample.

The Uncertainty Quantification (UQ) session was broken into two categories: nuclear data uncertainty quantification and the use of that uncertainty quantification. Thematic to the UQ session was the loss of information when going from nuclear data measurement, to evaluation, to evaluated file, and finally to neutron transport calculations. Current evaluated ND libraries typically only contain covariances, which assume that the probability distributions are Gaussian. Beyond being a simplified assumption for many evaluations, this can lead to negative values on many observables when attempting to sample the covariance. The covariance format, however, is very efficient in that a simple set of linear equations can transform uncertainty from parameters or cross sections to the application of interest. Focused collaboration is needed between nuclear data evaluators and nuclear data users to ensure that needs are being met.

1. INTRODUCTION

WANDA2024 is the eighth WANDA workshop. These workshops bring together key parts of the ND community, including ND producers, users, and program managers. The goal of these workshops is to identify and prioritize ND needs and determine actionable strategies to address those needs. Some of the needs identified by WANDA2024 survey responses are shown in Fig. 1.

The first two workshops in this series were the Nuclear Data Needs and Capabilities for Applications (NDNCA) workshop in 2015 and the Nuclear Data Exchange Meeting (NDEM) in 2016. After the NDNCA workshop, the Nuclear Data Working Group (NDWG) was founded to facilitate crosscutting collaboration between programs, made up of representatives designated by program managers with interest in nuclear data needs. These needs, priorities, and potential funding mechanisms were presented to federal program managers during NDEM, after which the Nuclear Data InterAgency Working Group (NDIAWG) was founded. The NDIAWG is composed of federal program managers who are interested in addressing nuclear data needs with the goal to coordinate nuclear data funding between participating program offices. The NDIAWG is chaired by the US Department of Energy (DOE) Office of Science, Nuclear Physics (NP).

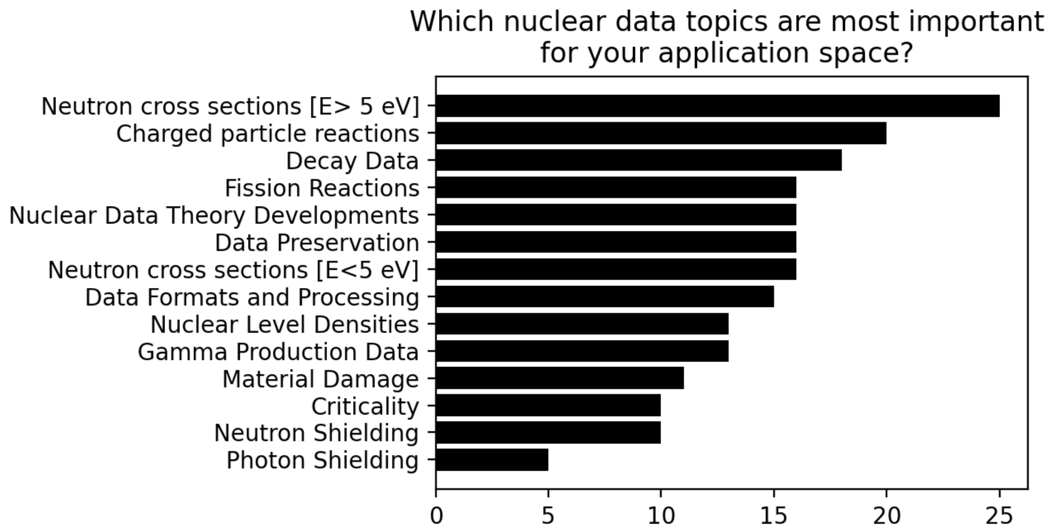

Figure 1. Attendees of WANDA 2024 were surveyed following the meeting. Responses indicated that attendees found that their application space required many aspects of ND, most strongly for neutron cross sections, charged particle reactions, and decay data.

Following NDEM, the first NDIAWG funding opportunity announcement (FOA) was released and managed by DOE NP. These FOAs are now released annually and are developed from the recommendations of the WANDA workshops. Over $**60 million** in nuclear data investments have been made since the release of the first NDIAWG FOA in 2018, all of which have directly affected applied science areas. This level of effort has only been realized through a collaborative funding effort of multiple programs interested in nuclear data. The new-start projects for fiscal year (FY) 2024 included the following topics:

- Accelerated Decay Data Evaluation and Development of an Adopted Decay Data Library
- Benchmarking and Validating Cosmogenic Activation Models
- Development of Benchmark Measurements for Capture Gamma Cascades
- Impact of Nuclear Data on Advanced Nuclear Energy Systems Safety and Operation
- The Berkeley Atlas: A Database of Absolute Cross Sections for Inelastic Gamma-Ray Production with 14 MeV Neutrons

WANDA2024 followed a format similar to the previous several WANDA meetings. A plenary session was held to kick off the meeting, where federal program managers are encouraged to share the ND needs of their offices and US and international collaborators give invited talks. WANDA2024 was unique compared with previous years because it had a dedicated focus on FES ND needs. Historically, WANDA has been attended by researchers focusing on fission-based applications, and the introduction of FES topics had the effect of expanding the diversity of voices at WANDA. The postworkshop survey showed that about 30% of WANDA2024 participants were attending for the first time (see Fig 2). In an effort to bridge some of the ideas and language used in the nuclear fission and fusion communities, an overview of the nuclear data pipeline was one of the invited lectures. The opening plenary session was followed by five serial sessions covering three FES topics, ND needs for isotope production and targetry, and uncertainty quantification. An all-day plenary session was held on Thursday in which principle investigators of NDIAWG FOA-funded projects were able to highlight their research accomplishments and discuss their future efforts. The workshop ended with summaries and recommendations from each of the five road-mapping sessions.

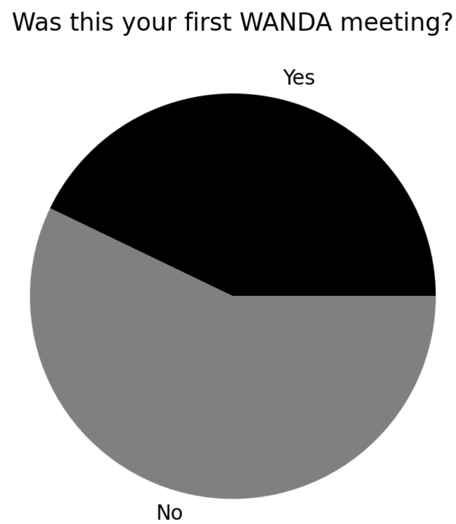

Figure 2. Many of the attendees WANDA 2024 were new to the WANDA community, indicating a growing community of practitioners interested in improving the quality of ND.

2. GOALS OF THE NDWG AND NDIAWG

The NDWG membership is currently around 50 members. Each interested federal program can nominate up to two experts in nuclear data or applications from the national laboratories who represent the program or laboratory mission interest within the NDWG, which ensures that program-specific needs are communicated between the laboratories and the NDWG. In addition to the nominations by the federal program managers, each DOE and National Nuclear Security Administration (NNSA) national laboratory is able to nominate up to two individuals to represent their missions and communicate opportunities back to their home institution.

The NDWG is then responsible for determining the scope of the road-mapping sessions held during the WANDA workshops to facilitate the goals of the group and program managers. The chosen topics are based on current national priorities, funding agency mission goals, and input from the greater nuclear data community. These road-mapping sessions gain consensus from the workshop participants on crosscutting nuclear data needs and actionable recommendations that will improve nuclear data for applications. These recommendations are recorded in proceedings such as this and are used to guide the NDIAWG FOA topics. Proceedings from previous WANDA workshops can be found on the NDWG website [1]. The NDWG website additionally contains other publications and resources that are useful to the broader nuclear data community.

The NDIAWG is open to all interested federal program managers across DOE, NNSA, the National Aeronautics and Space Administration, National Institutes of Health, the US Department of Defense, and other funding agencies. Membership has grown to 17 agencies since 2018, and for 2024, the FES office was heavily targeted for participation in WANDA. The NDIAWG communicates regularly on nuclear data needs, coordinates planned projects, and meets about quarterly. The NDIAWG releases an annual nuclear data FOA aimed at creating crosscutting funding opportunities that are co-funded across the NDIAWG agencies. Throughout the years, these FOAs have been very successful at funding a significant number of nuclear data projects across a wide variety of application areas. Active projects are highlighted in a review session at the end of each WANDA workshop, which has been overviewed in the following section.

3. PLENARY SESSIONS FOR WANDA 2024

3.1 INTERAGENCY NUCLEAR DATA TALKS

One of the strengths of the WANDA workshop is the diversity of ND and application spaces discussed, and this was well represented by the group of program managers that presented during the plenary session. This group included representation from DOE NP, the White House Office of Science and Technology Policy, DOE FES, DOE Isotope R&D and Production (IP), NNSA NA-22, NNSA NA-113, NNSA NA-114, the Nuclear Criticality Safety Program (NCSP), and the Defense Threat Reduction Agency (DTRA).

From a high-level viewpoint, several targets were identified for increased investment and enhanced stewardship in alignment with DOE NP Nuclear Science Advisory Commitee (NSAC) goals, including the following:

- Workforce development
- Ongoing fission evaluations
- Accelerated decay data evaluations
- Improved reaction modeling with better links to nuclear structure
- Neutron-induced data from low- to mid-energies
- High-energy reactions and material stopping power

Along with this high-level ND target list, several new areas of opportunity were identified as fusion energy, space exploration, nuclear energy (fission), medical applications, and infrastructure (e.g., workforce, database modernization).

Specific nuclear data needs were raised, most of which had significant overlap across different nuclear programs. DOE FES reiterated the importance of nuclear data for the FES program and stated a need for better neutron damage cross sections using examples of magnet materials, tungsten, and reduced-activation ferritic-martensitic (RAFM) steels. They also conveyed needs for reduced ND uncertainties for the tritium breeding ratio (TBR), benchmark measurements, and a 14 MeV fusion prototypic neutron source to produce such measurements. DOE IP identified needs for low-energy neutron capture cross sections and charged-particle cross sections up to 200 MeV. They also reinforce the need to reinvigorate the ND workforce. The NNSA NA-22 program needs include cross section, total neutron yield and neutron spectrum, and gamma emissions from (α, n) reactions with reduced uncertainties (high priority for ^{27}Al and ^{17,18}O). NA-22 also expressed the need for measurements of ^{238}Pu, ^{240}Pu, and ^{242}Pu spontaneous fission half-lives; prompt fission neutron spectra; nu-bar; and multiplicity distributions with uncertainties $<1\%$, as well as improved independent and cumulative fission product yields. DTRA expressed needs for updated cross section data for ThLiYCl detector materials and improved uncertainties for neutron shielding materials. Both NA-11 and NA-22 expressed the need for improved reaction cross sections on radioactive nuclides—particularly fission products.

3.2 THE NUCLEAR DATA PIPELINE

Modern nuclear applications require detailed and complex modeling using computer codes such as MCNP and SCALE. These codes rely on evaluated nuclear data libraries to describe the detailed nuclear (reaction or decay) events in these simulations. This presentation gave an overview of the process by which nuclear experimental and theoretical results are integrated into evaluated data libraries for use in nuclear applications.

This entire process is informally known as the “Nuclear Data Pipeline.” In addition to theory and experiment, this “Pipeline” includes some other important steps, such as benchmarking the libraries, in which user codes are used to test library performance in simulations of real-world systems, and sensitivity studies, which are used to locate data deficiencies and assess their effects on user problems. The entire “Nuclear Data Pipeline” is coordinated by the US Nuclear Data Program for nuclear structure data and the Cross Section Evaluation Working Group for nuclear reaction data—specifically, the Evaluated Nuclear Data File (ENDF) nuclear data library.

3.3 FOA-FUNDED PROJECT OVERVIEWS

To provide program managers an overview of the work funded on previous calls from the NDIAWG, 18 project summaries were presented. These presentations were designed mostly in a “lightning round” style with very brief overviews on progress made by the different groups. The projects covered a broad range of ND topics, including fission product yields, γ production cross sections and γ-ray cascades, β-decay measurements and models, measurements that resolve ND discrepancies, photodisintegration of tritons, improvements to user access to US nuclear structure and decay data libraries, cosmogenic activation modeling, ND for advanced nuclear energy systems, α-induced reactions on light nuclei, measurements of spontaneous fission of Pu, and nuclear reaction cross sections on short-lived fission products. Details on the presented work is given in App. A.6.

4. HIGHLIGHTS AND RECOMMENDATIONS FROM THE ROAD-MAPPING SESSIONS

Detailed road-mapping session summaries can be found in App. A. The following subsections present brief session overviews and the recommendations from each session.

4.1 FES: FUSION NEUTRONICS

Session Chairs: Keegan Kelly, Laura Gustad, and Michael Loughlin

Modeling and simulation of fusion energy sources will involve a range of charged particle and neutron reactions. Fusion energy reactors based on deuterium–tritium (D-T) fusion reactions will produce intense sources of high-energy (14 MeV) neutrons, and these neutrons will interact with the surrounding materials, causing potential radiological and engineering hazards. Nuclear engineers must answer several questions to accurately model future applications. What are the anticipated reactions for energy production, and do specific data needs exist? What are the products of these reactions, and are there data needs for understanding secondary reactions? Do gaps exist in current neutronics code capabilities to accurately model the interactions? ND must accurately predict shielding, activation, dose rates, and neutron diagnostics. What data are necessary to operate neutron sources (e.g., International Fusion Materials Irradiation Facility, Fusion Prototypic Neutron Source)?

The Fusion Neutronics session posed these questions to the community throughout the presentations and collected detailed feedback from the participants. After this session, the community made the following recommendations:

- Recommendation 1: Perform additional detailed sensitivity studies of fusion reactor designs identifying nuclei and nuclear reactions for which nuclear data quantities are insufficient for guiding and validating reactor design. Priority lists for these data should be given in the context of economics of the reactor design (e.g., is there a reaction uncertainty that indicates an expensive change in the design?) and those that prevent accurate determinations of performance and safety of reactor designs. Nuclear data areas of focus were generally agreed to be Be, Li, Pb, and structural materials (particularly, steel and steel alloys), but more quantitative and ordered descriptions of the effect of current nuclear data uncertainties from these elements would be ideal. If possible, energy spectra of neutrons interacting with important nuclei via important reactions should also be provided to guide experimental measurements of these reactions.
- Recommendation 2: Funding should be made available for evaluator efforts to survey which of the nuclei and nuclear reactions identified in fusion reactor sensitivity studies are (a) in need of new measurements to be included in evaluations or (b) in need of a new evaluation only if modern, quality data already exist but just have not been included in recent evaluations. Evaluation of nuclei for which sufficient data exist should also be made available with encouragement to provide covariances for the new evaluations if possible. Further conclusions on this point include the following:
  - Modern evaluations of light elements do not currently reach 14 MeV, but paths forward to achieve this are being pursued.
  - Medium/heavy element evaluations of Co, Cu, Mo, Nb, Sn, Ni, Mn, Ti, and V were highlighted as needing attention because of measurement needs, length of time since the last evaluation, method of past evaluation, or combinations of these reasons.
  - Pulsed sphere benchmark measurements of Li, C, O, Mg, Al, Ti, Fe, Pb, and Be were highlighted as needing changes to match data.

- Recommendation 3: Funding opportunities for differential, integral, and benchmark-type measurements should be made available for measurements of nuclei and specific nuclear reactions identified as both (a) high-priority for reactor design simulation and economics and (b) in need of new data to produce reliable evaluations. Covariances for these data must be provided in the final data, including a complete uncertainty quantification for relevant parameters of the experiments, and these covariances must be communicated to evaluators directly to ensure reliable inclusion. Further conclusions on this point include the following:
  - Measurements of the ^{9}Be(n,2n) and ^{208}Pb(n,2n) reactions were discussed as high priority.
  - The need for an accessible and reliable reference reaction measurement was discussed, with preference to monoisotopic nuclei with well-understood level structure/γ emission of the daughter nuclei.
  - Neutrons in DT fusion reactors are created with a mean energy of 14 MeV, but differential measurements should not be limited to just this energy range because (a) neutrons lose energy in the reactor medium, and therefore, the relevant distribution of incident neutrons extends to lower energies, including the 2.45 MeV D-D fusion neutron energy, and (b) nuclear data at a single energy point are potentially subject to unknown systematic errors that would not be obvious unless multiple energies are measured.
- Recommendation 4: A summary of all fusion-relevant integral experiments should be compiled. An assessment of the quality of these experiments as benchmarks should be made. Recommendations on improving the quality or the need for further experiments should be provided.
- Recommendation 5: A decision on a high-fluence neutron source should be made. This is not a decision about if or how a neutron source should be provided but when.
- Recommendation 6: Workforce development is of paramount importance in the areas of evaluations, neutron source development and exploitation, and design and operation of fusion facilities.
- Recommendation 7: Information should continue to be exchanged between nuclear data and fusion communities.
- Recommendation 8: A repository of the facilities available for nuclear data measurements/experiments should be created. Appendix A of the *Second Report of the Nuclear Data Charge Subcommittee of the Nuclear Science Advisory Committee* provides a starting point. A repository should be updated annually with changing capabilities, hours offered, and commercial facilities included for the nuclear data and fusion communities to reference as a resource for which facilities could support the experiments recommended above.

4.2 FES: TRITIUM PRODUCTION

Session Chairs: Paul Humrickhouse, Sofia Quaglioni, and Stephanie Lyons

Tritium, or ^{3}H, spontaneously decays to ^{3}He with a 12.3-year half-life. Amounts of this isotope generated in Canada Deuterium Uranium–type reactors are insufficient to meet the estimated needs for fusion. The availability of adequate resources of externally bred tritium for the reactor start-up and tritium self-sufficiency (i.e. the self-sustaining production of tritium in breeding blankets as part of the overall reactor cycle) are major requirements for the viability of future fusion power plants based on D-T fuel. The session on tritium production was aimed at resolving the following questions:

1. Can production processes or reactor materials be used to establish a source of tritium for fusion energy applications?
2. Which nuclear data are necessary to support testing and operation of breeder blankets?
3. Is the accuracy of nuclear data sufficient to predict activation of breeder blankets?
4. What are the uncertainties and sensitivities to the tritium breeding ratio?
5. Can nuclear cross sections be used to accurately predict transmutation of materials in blankets?

Topics discussed during the session included the NNSA tritium modernization program; alternative pathways for tritium production; tritium blanket design and materials; challenges to achieving tritium self-sufficiency; differential measurements of neutron-induced reactions for tritium production; predictive theory of neutron-induced reactions for tritium production; high-flux D-T neutron sources for tritium breeding experiments; and integral experiments for benchmarking tritium breeding.

Following this session, the community made the following recommendations:

- Funding should be provided for a scoping study to identify and narrow down the specific nuclear data inventory, including required uncertainties and priorities, for breeder, multiplier, and structural materials used in US fusion reactor and breeding blanket designs. This will require (1) a survey of existing studies on the nuclear data uncertainties in calculations of the achievable TBRs and their comparison with available benchmark tests in Europe and Japan and (2) new complementary sensitivity studies (with full propagation of nuclear data uncertainties) of TBRs for blanket materials used in US magnetic fusion energy and inertial fusion energy fusion reactor concepts.
- Funding should be provided to assess the status of differential measurements, predictive simulations, and phenomenological analyses for tritium production–relevant nuclear data and their ability to fill gaps in evaluated means and covariances for cross sections, angular distributions, and exit-channel product information, particularly in the intermediate and fast-neutron energy regime. Such assessment will help identify priorities for new measurements and calculations to improve nuclear data libraries.
- We recommend a third scoping study to build a path toward integral benchmarks for neutron energies and fluxes relevant for tritium production in US blanket designs. A survey of existing relevant integral and diagnostic data at national laboratories and other US programs is needed to help define and narrow down the best integral experiments; initial integral experiments for US blanket subassemblies by leveraging current facilities that can offer high fusion neutron fluxes should be conducted to provide guidance for the development of fusion integral benchmarks.
- A funding mechanism to facilitate and stimulate exchange of information and collaboration among the fusion energy, defense, and nuclear data communities will be essential to accelerate the path to tritium self-sufficiency while also supporting commercial tritium production for maintaining the US nuclear weapons stockpile.
- Access to advanced high-performance computing architectures and collaborative funding mechanisms to strengthen quality and support the continuous development of software used across the nuclear data pipeline will be essential to assess the viability of future commercial power plants and continue to support the US nuclear deterrence mission.

4.3 FES: MATERIAL DAMAGE

Session Chairs: Paul Romano and Paul Wilson

Nearly every region of a fusion reactor will be subject to intense neutron irradiation, including plasma-facing components, structural materials, blankets, and magnets. Over time, the production of defects from high-energy neutrons will degrade material performance, adversely affecting the safe and economic operation of these systems. Defect production in materials is highly sensitive to the underlying nuclear data used, and thus, accurate and reliable nuclear data are essential to predicting material damage. The goal of this session was to assess the state of nuclear data affecting damage calculations. In particular, the following charge questions were put forth: What nuclear data needs exist for estimates of displacement-per-atom (dpa) rates? What gas-producing reactions are not adequately captured in current data libraries? How accurate are radiation damage models, and what improvements are needed in models, uncertainties, and processing or transport codes? What experimental capabilities are available or needed to validate predictions of damage? Finally, what does the materials community view as important for the nuclear data community to provide to accurately assess materials damage?

Following this session, the community made the following recommendations:

- Further work is needed to bridge scales between nuclear data or particle transport and materials modeling while accounting for underlying uncertainties. The research and development community in the US is well-positioned to make inroads in this area to complement ongoing work in Europe.
- Improvements are needed in the coverage and quality of recoil distributions in current evaluations. Poor-quality and missing recoil distributions continue to be an issue in many evaluations. Both can be harmful; missing recoil distributions force nuclear data processing codes to make assumptions, whereas recoil distributions that are present but have not been properly vetted can result in nonphysical behavior.
- Sanity checks on recoil distributions should be added either to nuclear data processing codes or in the evaluation acceptance processes to mitigate the possibility of generating erroneous displacement cross sections before they affect downstream users.
- Scoping studies should be carried out to identify outstanding data needs for materials damage and assess how much effort addressing each would take (and if relevant capabilities—experimental, computational, or otherwise—are already available). Based on this information, sponsors could determine a set of prioritized activities.
- Sensitivity and uncertainty quantification studies are needed to better understand what ultimately drives uncertainties for damage calculations.
- The arc-dpa damage metric is becoming increasingly accepted in the damage modeling community and should be properly integrated into data processing and simulation codes. Existing codes are hardwired for the legacy NRT-dpa metric, which tends to overpredict dpa because it neglects athermal recombination effects.
- Nuclear data end users do not have an easy, straightforward way to report issues with evaluations. An open-source repository for evaluations would facilitate better interaction with users and give them a means to report issues.

4.4 ISOTOPES AND TARGETRY FOR NUCLEAR DATA

Session Chairs: Ellen O'Brien, Etienne Vermeulen, Khachatur Manukyan, and Matthew Gott

This session incorporated perspectives from experimenters using targetry for the collection of nuclear data as well as individuals creating these targets. The experimenters highlighted challenges encountered when using radioactive and highly enriched materials in application-specific geometries for the collection of nuclear data for nonproliferation, astrophysics, and fusion applications. Themes noted in their talks were the needs for radioactive and high-purity enriched stable targets, adequate target characterization to reduce uncertainties, and measurements on short-lived radioactive nuclei. The target makers provided updates on their recent research contributions to the field of target fabrication and how these unique and novel target fabrication technologies could be utilized to benefit the nuclear data community. Techniques highlighted were 3D printing with spherical powders, combustion synthesis coupled with spin coating and electrospraying, inkjet printing, and isotopic doping. These speakers also illustrated their plethora of target characterization capabilities, including scanning electron microscopy, focused ion beam microscopy, and energy-dispersive x-ray microscopy, x-ray diffraction, x-ray fluorescence, x-ray photoelectron spectroscopy, and transmission electron microscopy.

Following this session, the community made the following recommendations:

- Recommendation 1: The next generation is needed to ensure that researchers have continuity in capabilities for different target fabrication techniques. Workforce development is a clear challenge faced by the community—only a handful of individuals in this field possess this knowledge, and training the next generation is a must to ensure that this knowledge is not lost. A diverse set of backgrounds and education levels will be required, including trades, material science, chemistry, physics, and engineering. The recommendation is that investment in workforce pipeline development and target fabrication facilities is needed both at the national laboratories and, more importantly, at the universities.
- Recommendation 2: A universal message from the community is that target characterization is critical to the success of any nuclear data experiment. Inaccurate or inadequate target characterizations can cause unacceptable uncertainties or create artifacts in the data that destroy its viability for use by the community. It is recommended that there be investment in target characterization techniques, including quantifying isotopic purity, uniformity, mass, and thickness.
- Recommendation 3: In the discussion, it was highlighted that target information has not historically been provided in all publications. A request from the experimenters was that there be some way to store information on target characteristics as well as what experiments they have been used in. It is recommended that there is investment to create a database of target information, similar to the Nuclear Science User Facility database, so that target fabrication and characterization details are easily searchable by the community in concordance with the recent DOE Office of Science and Technology Policy memo on data preservation requirements.
- Recommendation 4: The target needs survey identified that numerous isotopes and specific target forms of enriched isotopes (listed in Appendix A) are needed by the community. It is recommended that funding be directed to help produce these needed isotopes and in a form that the nuclear data community requires.

4.5 UNCERTAINTY QUANTIFICATION

Session Chairs: Nathan Gibson, Denise Neudecker, Robert Casperson, and Ugur Mertyurek

Understanding nuclear data's inherent uncertainties and the propagation of those uncertainties to applications are active areas of interest across all disciplines making use of ND. This session sought to highlight the identified biggest needs to enable proper uncertainty quantification of ND from theory and experiment through evaluation and all the way to end users. The incomplete and inconsistent quality of existing covariance information poses a large challenge for those well-versed in the uncertainty quantification field. For those newer to this field, complications regarding the meaning and trustworthiness of covariance data, as well as the complexity of techniques for forward propagation, require training and resources from those established in the community. By hearing from those that have pioneered many of the important aspects of this work and from those that would benefit from future work, this session made the case for the exciting and modern approach of uncertainty quantification–oriented ND work.

This session heard from the user community in advanced reactor design, nuclear criticality safety, defense programs, and nuclear forensics. Each of these disciplines highlighted the benefits of improved covariances and uncertainty quantification workflows via improved predictions for applications, enabling prioritization of future nuclear data efforts and reliable and defensible uncertainty estimates.

One recommendation that unifies under its umbrella many issues that were highlighted of key importance within this session was that **medium fidelity covariances** should be created and made available for cross sections and other observables (e.g., angular distributions). Similar to low-fidelity covariance efforts of the past, the goal should be to fill in missing covariances from the ENDF database with well-reasoned and documented estimates of uncertainties. With the availability and future development of supporting tools, these covariances should include not only theory information but also fold in experimental observations in a semiautomated manner. Futhermore, the development of this capability and of the medium-fidelity covariances will serve as a mechanism for improving quality assurance of existing covariances. The ingredients needed to achieve this recommendation include the following:

- Experimental uncertainties need to be quantified thoroughly and consistently, for instance, via templates of experimental uncertainties or exploring missing uncertainty sources for RRR evaluations. Tools and formats to simplify (and partially automate) experimental UQ and store all relevant information should be developed. Modernization of the EXFOR format and compilations can also improve experimental UQ by including more relevant uncertainty information in EXFOR, as well as storing experimental data used for the evaluation in a companion database to EXFOR.
- Theory uncertainties need to be studied, including both uncertainties in model parameters and uncertainties in the model forms. Because much of the missing covariances in ENDF are for observables with limited experimental data, robust estimates of uncertainties from theory are key.
- Evaluation methodologies need to be reviewed. Changes in mean values and covariance flowing only from employing different evaluation methodologies need to be understood.
- A capability for semiautomation of covariance generation must be developed. A medium-fidelity covariance library is a monumental and likely intractable task if time-consuming human effort is required for each observable. Through automation of these procedures, a greater number of observables can be addressed, additional consistency can be obtained, and better quality assurance can be achieved.

Users and producers also highlighted the following needs in how to use and access covariances:

- The community needs to implement and perform rigorous quality assurance of covariances. It was mentioned as one example that systematic comparison of uncertainties across evaluated ND libraries could help pinpoint issues. Methods to correct underestimated evaluated uncertainties are also needed .
- Low-barrier access to EXFOR and evaluated data and covariances is key for new users coming into the field. Tools to support that access are needed.
- Establishing covariance and UQ training for users was highlighted again and is partially being addressed by a recent funding call by the NDIAWG.

When nuclear data covariances are being used for adjustment or sampling, the following needs were identified:

- Hosting and distributing replica evaluated nuclear data ensembles would be of high interests for users.
- Covariances between integral experiments need to be quantified.

- Users highlighted the need for verification and cross-validation studies for large-scale adjustment.
- Creating adjustment tools for general users was discussed.
- Expanded sensitivity capabilities and readily available tools are needed to identify the most important observables for user cases.

This topic is of perennial interest to the nuclear data community, and this was not the first time similar subject matter has been discussed via WANDA and similar events. In 2018, the Nuclear Data Roadmapping and Enhancement Workshop (NDREW) included the topic of "Uncertainty, Sensitivity, and Covariances." In 2020, WANDA included the session "Covariance/Sensitivity/Validation." In 2022, WANDA included the topic "Nuclear Data Adjustments and Impact on Applications."

These past sessions culminated in a small, invitation-only, focused workshop called the Nuclear Data Uncertainty Quantification Working Meeting (NDUQWM) [2], which took place virtually on October 11–13, 2022. This meeting was organized through the NDWG per a request from the DOE Office of Science. The goal of this meeting was to write a "White paper for 5—10 Year Priorities on the Topic of Nuclear Data Covariances and Uncertainty Quantification for Users." Input was collected from 30 invited participants spanning experts in nuclear data covariance production to various application areas. Because this meeting was by invitation only, this year's WANDA meeting gave the opportunity for the whole community to revisit the main findings of NDUQWM. In general, these priorities were confirmed, but additional needs were highlighted, as well.

Finally, the topic of uncertainty quantification and covariances is of broad interest, spanning users and producers. Despite the numerous sessions at previous meetings, a large scientific meeting on the topic with a call for in-depth scientific papers might help motivate future developments.

In summary, the community made the following high-priority, crosscutting recommendations, matching those already listed in [2]:

- Medium fidelity covariances
- Quality assurance of covariances
- Improved experimental UQ
- Covariance and UQ training for users
- Adjustment tools for general users

5. SUMMARY

The WANDA2024 workshop brought together ND researchers from a diverse set of application spaces and scientific disciplines to discuss pressing ND needs. In addition to the important topics of isotope science and uncertainty quantification, this year's workshop had a special focus on ND supporting applications of interest to the DOE FES program. This focus resulted in an increase of fusion energy scientists attending and contributing to the workshop and new ideas and needs being identified. The ND needs of the nuclear science community were diverse, but many of the needs identified were synergistic in nature, and common gaps were identified. Many users require tools and training to quantify application sensitivity to ND. Once the most sensitive and effective ND are identified, the quality of these ND and uncertainties need to be assessed and, when necessary, reevaluated or remeasured. Maintaining a critical mass of talented scientists in the ND field by attracting new researchers is essential to all the various components of the ND community.

REFERENCES

[1] D. Brown, “Nuclear data working group,” 2024. [Online]. Available: https://www.nndc.bnl.gov/ndwg/

[2] D. Neudecker, R. C. Little, L. Bernstein, R. Bostelmann, D. Brown, R. Casperson, S. Croft, S. Dewji, N. Gibson, L. Greenwood, P. Griffin, L. Kyriazidis, A. Lewis, M. Pigni, B. Pritychenko, B. Rearden, J. Ressler, C. Romano, T. Slaba, M. Smith, V. Sobes, A. Sonzogni, S. A. V. Wiel, N. Vassh, A. Voyles, and K. Wendt, “ White paper for 5–10 Year Priorities on the Topic of Nuclear Data Covariances and Uncertainty Quantification for Users ,” Los Alamos National Laboratory, Tech. Rep. LA-UR-23-27944, 2024.

[3] M. R. Gilbert and J.-C. Sublet, “Differential DPA calculations with SPECTRA-PKA,” *J. Nucl. Mater.*, vol. 504, pp. 101–108, 2018.

[4] M. J. Norgett, M. T. Robinson, and I. M. Torrens, “A proposed method of calculating displacement dose rotes,” *Nucl. Eng. Des.*, vol. 33, no. 1, pp. 50–54, Aug. 1975.

[5] K. Nordlund, S. J. Zinkle, A. E. Sand, F. Granberg, R. S. Averback, R. Stoller, T. Suzudo, L. Malerba, F. Banhart, W. J. Weber, F. Willaime, S. L. Dudarev, and D. Simeone, “Improving atomic displacement and replacement calculations with physically realistic damage models,” *Nat. Commun.*, vol. 9, p. 1084, 2018.

[6] R. MacFarlane, D. W. Muir, R. M. Boicourt, A. C. Kahler, and J. L. Conlin, “The NJOY nuclear data processing system, version 2016,” Los Alamos National Laboratory, Los Alamos, New Mexico, Tech. Rep. LA-UR-17-20093, 2017.

[7] S. Chen, D. Bernard, L. Tamagno, O. Litaize, and P. Blaise, “Uncertainty assessment for the displacement damage of a pressurized water reactor vessel,” *Nucl. Mat. Energy*, vol. 28, p. 101017, 2021.

[8] S. Chen and D. Bernard, “Recommendation for computing neutron irradiation damage from evaluated nuclear data,” *J. Nucl. Mat.*, vol. 562, p. 153610, 2022.

[9] S. Chen, Y. Peneliau, and D. Bernard, “Comparison of evaluated nuclear data for neutron irradiation damage calculation in fusion spectra,” *Fusion Eng. Des.*, vol. 171, p. 112594, 2021.

[10] D. Neudecker, B. E. Hejnal, F. Tovesson, M. C. White, D. L. Smith, D. E. Vaughan, and R. Capote, “Template for estimating uncertainties of measured neutron-induced fission cross-sections,” *EPJ Nuclear Sciences and Technologies*, vol. 4, no. LA-UR-17-29963, 2018.

[11] J. Batchelder, S.-A. Chong, J. Morrell, M. A. Unzueta, P. Adams, J. Bauer, T. Bailey, T. Becker, L. Bernstein, M. Fratoni *et al.*, “Possible evidence of nonstatistical properties in the ^{35}Cl(n, p)^{35}S cross section,” *Physical Review C*, vol. 99, no. 4, p. 044612, 2019.

[12] S. A. Kuvin, H. Y. Lee, T. Kawano, B. DiGiovine, A. Georgiadou, C. Vermeulen, M. White, L. Zavorka, and H. I. Kim, “Nonstatistical fluctuations in the ^{35}Cl(n, p)^{35}S reaction cross section at fast-neutron energies from 0.6 to 6 MeV,” *Physical Review C*, vol. 102, no. 2, p. 024623, 2020.

[13] J. N. Warren, “^{35}Cl (n,p) reactions in a ^{6}Li enhanced CLYC detector,” Master’s thesis, Ohio University, 2021.

[14] M. C. Kennedy and A. O’Hagan, “Bayesian calibration of computer models,” *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, vol. 63, no. 3, pp. 425–464, 2001.

[15] G. Schnabel, H. Sjöstrand, J. Hansson, D. Rochman, A. Koning, and R. Capote, "Conception and software implementation of a nuclear data evaluation pipeline," *Nuclear Data Sheets*, vol. 173, pp. 239–284, 2021.

[16] Y. Yamauchi, L. Buskirk, P. Giuliani, and K. Godbey, "Normalizing Flows for Bayesian Posteriors: Reproducibility and Deployment," *arXiv preprint arXiv:2310.04635*, 2023.

[17] K. Godbey, L. Buskirk, and P. Giuliani, "BMEX - The Bayesian Mass Explorer (v1.0.0)," [Computer Software] https://doi.org/10.5281/zenodo.8317327, 2023. [Online]. Available: https://doi.org/10.5281/zenodo.8317327

[18] D. Phillips, R. Furnstahl, U. Heinz, T. Maiti, W. Nazarewicz, F. Nunes, M. Plumlee, M. Pratola, S. Pratt, F. Viens *et al.*, "Get on the BAND wagon: a Bayesian framework for quantifying model uncertainties in nuclear dynamics," *Journal of Physics G: Nuclear and Particle Physics*, vol. 48, no. 7, p. 072001, 2021.

[19] J. Gordon, J. Batchelder, L. Bernstein, D. Bleuel, C. Brand, J. Brown, B. Goldblum, B. Frandsen, T. Laplace, and T. Nagel, "GENESIS: Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1061, p. 169120, 2024.

[20] S. Marin, C. A. Bravo, I. E. Hernandez, M. J. Devlin, K. J. Kelly, J. M. O'Donnell, S. D. Clarke, and S. A. Pozzi, "Event-by-event Neutron-Gamma Multiplicity Correlations in ^{242}Pu(sf)," INMM 2021 Annual Meeting Proceedings, 2021.

APPENDIX A. DETAILED ROAD-MAPPING SUMMARIES AND OUTCOMES

APPENDIX A. DETAILED ROAD-MAPPING SUMMARIES AND OUTCOMES

This appendix provides all of the detailed session summaries from WANDA2024. An overview of the recommendations from each session can be found in Sec. 4.

A.1 FES: FUSION NEUTRONICS

A.1.1 Importance of Nuclear Data for Activation Calculations of Fusion Systems and Key Differences from Fission

Speaker: David Foster (UK Atomic Energy Authority)—david.foster@ukaea.uk

During this talk, the author discussed how nuclear activation calculations can be affected by how the inventory equation is integrated. The focus was on highlighting subtle differences between fusion and fission of different integration approaches, pointing out that fusion and fission require different effective models (integration). The author showed that the Chebyshev Rational Approximation Method (CRAM) and finite difference inventory integration methods lead to complete pathway transmutation graphs, which is important for both fission and fusion results to be correct. He also showed that certain implementations can cause short-lived nuclide errors (which is possibly caused by floating point precision or because of the graphical nature of nuclear data) and that these errors could be more important for fusion than fission. Results comparing different approaches based on Fusion Neutron Source (FNS) nuclide decay benchmarks were presented.

A.1.2 Impact of the Latest INDEN Cross Section in Fusion Applications and Update of the Fusion Evaluated Nuclear Data Library (FENDL)

Speaker: Tim Bohm (University of Wisconsin–Madison)—tim.bohm@wisc.edu

This talk presented the effects of using new candidate neutron cross section evaluations on fusion reactor relevant responses in realistic 1D cylindrical models of fusion reactors. It also summarized the International Atomic Energy Agency (IAEA) Fusion Evaluated Nuclear Data Library (FENDL). Descriptions of the fusion reactor designs that were modeled were provided and included the ITER and the Fusion Nuclear Science Facility (FNSF). Neutron cross section libraries that were compared included FENDL-3.1d, FENDL-3.2b, the Evaluated Nuclear Data File (ENDF)/B-VIII.0, and the latest International Nuclear Data Evaluation Network (INDEN) evaluations. Design-relevant responses that were compared included neutron flux, total nuclear heating (neutron+γ), and tritium breeding ratio. Gas production (H/He) was also compared but not shown. A brief description of the collaborative effort that produces the FENDL library was provided as well as a link to a recent journal paper that describes the FENDL library and validation process for the neutron sublibrary. Future work for FENDL development was also discussed and included developing more computational benchmarks, preparing consistent covariance data for sensitivity and uncertainty analysis, performing more validation on the deuteron and proton sublibraries, and developing more experimental benchmarks for the neutron, proton, and deuteron sublibraries.

A.1.3 Characterization of SHINE's High-Flux DT Neutron Source

Speaker: Ross Radel (SHINE Technologies)—rossradel@shinefusion.com

SHINE has evaluated the use of its 5×10^{13} n/s neutron source to perform tritium breeding experiments. This example used LiF–BeF_2 (FLiBe), assumed to be naturally enriched, heated to 900 K, and containing 45% of the 316H alloy of stainless steel and coolant (by volume) to account for heat management structure. This analysis suggests that the Fusion Linear Accelerator for Radiation Effects (FLARE) facility could generate 310 mCi of tritium in the FLiBe during a 50 h experiment within a 30 cm tall annular vessel with 50 cm thickness. This would result in 960 mCi of tritium per liter of FLiBe at the end of irradiation. This concentration of tritium in solution should be readily quantifiable, whether measured during a postirradiation evaluation or via an online measurement of flowing FLiBe during irradiation.

A.1.4 Nuclear Data for Neutron Sources and Diagnostics and Electronics

Speaker: Michael Loughlin (Oak Ridge National Laboratory)—loughlinmj@ornl.gov

A myriad of nuclear needs exist for diagnostics and electronics for fusion reactors and neutron sources. Accelerator-based neutron sources require improved nuclear data at energies for charged particle reactions at energies ≥ 55 MeV. Diagnostic aspects of fusion reactor operation require nuclear data (i.e., nuclear heating, gas production, transmutation) for a wide variety of materials including Au, Pt, Inconel 718, BN, pascalloy, and W. The development of dosimetry standards for neutron diagnostics and dosimetry fusion applications would be highly beneficial but is understandably difficult to obtain. Improved radiation transport accuracy modeling for shielding design and qualification of electronics is needed to properly validate benchmark studies.

A.1.5 Introduction to DoD Neutron Nuclear Data Needs

Speaker: Laura Gustad (Missile Defense Agency)—laura.gustad@mda.mil

Many government programs with nuclear environments also require advanced parts and use state-of-the-art microelectronic technology for improved performance. Nuclear environments include the full neutron spectrum, from thermal to fission to 14 MeV fusion neutrons with $> 1 \times 10^{10}$ n/(cm^2 s) flux across variable pulse lengths. Contemporary technology nodes have sufficiently low critical charge to be susceptible to thermal neutron–induced single-event upset. Additional neutron-induced single-event effects are possible in pulsed, high-flux 14 MeV neutron environments. None of the currently available neutron facilities provide 14 MeV neutrons at $> 1 \times 10^{10}$ fluxes with variable pulse lengths to fully characterize microelectronic parts against these environments. Coordination between the nuclear data, fusion, and US Department of Defense (DoD) communities can help drive national need for high-flux 14 MeV neutron sources and encourage cross-functional development. DoD is also working to develop neutron testing standards and work across agencies to understand testing needs via communication across the wider radiation community.

A.1.6 Nuclear Data Needs for the p-^{11}B Fuel Cycle

Speaker: Jed Styron (TAE Technologies)—jstyron@tae.com

Accurate and precise nuclear data are needed to improve the understanding, viability, and credibility of p-^{11}B fusion. Of interest is the cross section for the primary ^{11}B(p,2α)α reaction and secondary reactions, ^{11}B(α,n)^{14}N and ^{10}B(p,α)^{7}Be. An extensive search showed that nuclear data evaluations for these reactions were either missing; based on older, less accurate data; or had significant gaps at relevant particle energies. These findings were documented and shared with the nuclear data community at these proceedings, and newer experimental data from Sikora et al. was recommended for inclusion in the evaluation of the ^{11}B(p,2α)α cross section. Addressing the discrepancies identified for these reactions, among others, will add considerable confidence to derived quantities such as ignition conditions, radioactive material inventory, component lifetime, and facility radiation protection requirements.

A.1.7 Fusion-Relevant Light-Element Nuclear Data Evaluations

Speaker: Mark Paris (Los Alamos National Laboratory)—mparis@lanl.gov

This presentation discussed $\mathcal{R}$-matrix evaluations for some light-element compound systems (^{5}He and ^{6}He) in the context of recent efforts under the aegis of the NDIAWG. The presentation described the evaluation pipeline, which combines observed scattering and reaction data—unpolarized and polarized data—and its compilation and evaluation with the quantum-mechanically consistent $\mathcal{R}$-matrix (or Bloch–Green function) approach. Also, the presentation discussed the production of reaction cross section data and structure and decay parameter data, which are useful for applications across the nuclear security complex, in fusion nuclear energy applications, and for basic science. The presentation also discussed recent theoretical efforts to extend the range and utility of the $\mathcal{R}$-matrix approach to $(n,n'\gamma)$ and breakup reactions.

A.1.8 Evaluations for Medium- and High-Mass Nuclei for Fusion Applications

Speaker: Gustavo Nobre (Brookhaven National Laboratory)—gnobre@bnl.gov

The upcoming completion of ITER, a tokamak which will be the largest, most powerful fusion device in the world, highlights the need for targeted improvements of the nuclear data for transport calculations in materials relevant to fusion energy. Of particular relevance and interest are the structural materials found in many different steel alloys and in the strands that make the solenoidal electromagnets. The evaluations of such materials, which are often overlooked, present some unique challenges such as large cross section fluctuations that can happen at neutron energies as high as ~10 MeV due to the materials' low nuclear level densities. Examples of materials that could strongly benefit from a new evaluation are Nb, Sn, V, Ti, Mn, Ni, Co, Cu, and Mo.

A.1.9 Benchmarking of Fusion Data with Pulsed Sphere Experiments

Speaker: Robert Casperson (Lawrence Livermore National Laboratory), slides by Denise Neudecker (Los Alamos National Laboratory)—dneudecker@lanl.gov

Lawrence Livermore National Laboratory (LLNL) pulsed-sphere neutron-leakage spectra enable researchers to validate nuclear data from 3 to 15 MeV of several isotopes of interest for fusion research. For instance, measured spectra exist for light elements (e.g., ^{1}H, ^{2}H, ^{9}Be, ^{12}C, ^{16}O, ^{19}F) or structural materials (e.g., Ti, Fe, Pb). Researchers can explore the effect of elastic and inelastic cross sections and angular distributions along with the $(n,2n)$ reaction dependent on the material measured.

In the past, LLNL pulsed-sphere neutron-leakage spectra have been successfully used to find issues in nuclear data that might have eluded researchers otherwise. However, the experimental values are fairly uncertain (2%-8%) compared with criticality experiments, have poorly quantified uncertainties, and suffer from systematic biases. Given these issues, it might be worth remeasuring them. A careful analysis of experimental uncertainties would be of high importance to make the best use of the data for validation. Currently, the data are too biased and uncertain to reasonably use them for nuclear data adjustment. Also, angular distribution covariances and sensitivities of these spectra to angular distribution are missing to make use of these data for adjustment.

A.1.10 Neutron Facility Overview for Fusion Neutronics Nuclear Data Measurements

Speaker: Keegan Kelly (Los Alamos National Laboratory)—kkelly@lanl.gov

The recent emergence of fusion reactor technology has generated a myriad of nuclear data needs for neutron-induced reactions, and the nuclear physics experiment community is pursuing paths to respond to these needs. The production of data from the differential measurement facilities would begin the process of the nuclear data pipeline flow toward evaluation, compilation, and finally to the end-use calculations of fusion reactors themselves. White neutron sources and monoenergetic sources provide complementary measurements that can be used to cross-validate each other, thus enhancing the reliability of the nuclear data produced from these facilities. White neutron sources at the Los Alamos Neutron Science Center, Lawrence Berkeley National Laboratory, and Gaerttner LINAC facility at Rensselaer Polytechnic Institute as well as the monoenergetic neutron sources at Triangle Universities Nuclear Laboratory, University of Kentucky, and the

Edwards Accelerator Laboratory at Ohio University and the University of Massachusetts Lowell research reactor facility are all actively producing high-impact nuclear data and are available for future measurement campaigns to address the needs of the fusion reactor community.

A.1.11 Federal Program Interest

NA-11—National Nuclear Security Administration Research, Developent, Test, and Evaluation: Historically, NA-113 (OES) and NA-114 (ASC) have focused on fission-focused nuclear data neutron transport reactions for applications, but significant overlap exists between fusion science and the typical NA-11 portfolio, including but not limited to, Be and Li nuclear data, neutron scattering nuclear data on structural materials, and $(n,2n)$ reactions.

NA-22—Defense Nuclear Nonproliferation Research and Development (DNN R&D): Nuclear data needs under DNN R&D overlap the fusion science nuclei of interest for reactions on Fe, Cu, Pb, and W as first priority for elements for active interrogation and Li, Be, B, Cr, and Mn as a second priority. Nuclear data for Al, O, and Si are also of interest, though there are currently funded efforts to address these nuclear data needs. Given the recently created Nuclear Data portfolio of NA-22, efforts on measurements of reactions of interest for these elements should fit well into this new thrust.

DOE Office of Science—Fusion Energy Sciences (FES): The interest of FES in this session and all WANDA fusion sessions likely needs no explanation, but a desire for an intense prototypic neutron source was highlighted. The desire for such a source was echoed within the communities present, although also emphasizing that measurements should take place at other neutron facilities as well and not just at peak fusion neutron energies (see Recommendation 3, Sec. 4.1).

DOE Office of Science—Nuclear Physics (NP): NP highlighted a series of points of interest in the 2023 Nuclear Science Advisory Committee long-range plan for guiding additional investments that significantly overlap with the needs of the fusion reactor application, measurement, and evaluation communities, including

1. supporting structure evaluation capabilities;
2. enhancing reaction evaluation capabilities;
3. providing comprehensive, consistent neutron reaction and structure data; and
4. providing nuclear data for fusion energy.

The direct opportunity for nuclear data on structural materials was also highlighted and emphasized for overlap with space and fission-related nuclear data needs.

A.2 FES: TRITIUM PRODUCTION

A.2.1 Challenges in Achieving Tritium Self-Sufficiency

A determining factor for the viability of future deuterium-tritium (D-T) fusion energy power plants will be the self-sustaining production of tritium via absorption of the neutrons generated in the energy-production processes into breeding blankets (BBs). All breeding materials contain Li, and the production of tritium is realized with some combination of the ^{6}Li(n,T) and ^{7}Li(n,nT) reactions. Some BB concepts also include neutron multipliers, namely Be and Pb, with the multiplication achieved through (n,2n) reactions. To compensate for tritium losses (e.g., retention in structures, radioactive decay during operation, failure in the tritium processing system) and to provide excess inventory to enable the start-up of future reactors, the minimum required ratio of the rate of tritium bred in the blanket to the rate of tritium burned in the D-T reactions, known as the tritium breeding ratio (TBR), must be greater than 1. Furthermore, a reliable assessment with safety margins of the viability of reactor designs requires the calculated achievable values of the TBR to be equal or greater than this minimum required value. Larger safety margin values due to uncertainties in the calculated achievable TBR can result in higher reactor development and operational costs.

Factors influencing the calculated achievable TBR include engineering aspects (e.g., the choice of breeding materials and other materials used in the reactor's first wall and blanket and their arrangement, the confinement scheme used, the overall thickness of the blanket, or the type of blanket coolant) as well as uncertainties due to neutronics modeling and the underlying evaluated nuclear data involved in the calculations. Uncertainties associated with nuclear data are caused by uncertainties in evaluated neutron-induced reaction cross sections for elements found in the breeding, structural and coolant materials (including H, He, Be, O, N, C, F, Si, Cr, W, Ta, Ti, V, and Pb), as well as the energy and angular distributions of emitted secondary neutrons. Additional uncertainties can arise from the processing of the nuclear data (e.g., use of multigroup energy boundaries). Only limited work exists on the quantification of the nuclear data uncertainties of calculated achievable TBRs, and none exists for US breeding blanket designs. Estimates based on the available studies place these uncertainties between 3% and 8.6% depending on the BB design and materials. These are significant figures if one considers that overall uncertainties (including those from engineering and neutronics modeling aspects) add up to about 10% of the achievable TBR and that a 1% uncertainty in TBR translates into a shortage or surplus of 560 g of tritium per year for 1 GW of fusion power.

Uncertainties in the relevant nuclear data stem from both uncertainties in the experimental data and in the parameters of the nuclear models used for the evaluation, and these uncertainties are represented in the form of covariance matrices. Nuclear data (and covariance matrices especially) tend to be more mature and better evaluated in the thermal and low-energy region (below a few MeV) owing in part to decades of work in neutronics calculations for fission. Data are also typically available at 14 MeV, but intermediate energies in general present gaps in terms of missing or incomplete data, data of diminished quality, or underestimated uncertainties. This is a serious concern for tritium breeding calculations, which require nuclear data for the whole spectrum of neutron energies between $\sim$ 2 MeV and 14 MeV. For example, currently, only the combination of TALYS-based Evaluated Nuclear Data Library (TENDL) and Joint Evaluated Fission and Fusion File (JEFF)-3.3 libraries provides covariance data for all required nuclides. The lack or unreliability of covariance data is an obstacle in propagating the nuclear data uncertainties to neutronics calculations through perturbation theory methods or probabilistic random sampling (e.g., total Monte Carlo (TMC)) methods. The TMC method requires an intermediate step in the generation of random nuclear data samples that reproduce the covariance information stored in the nuclear data library. ND libraries only provide random ND samples in very limited cases (e.g., for $Z > 6$ isotopes in TENDL).

There is also very limited work on validating and verifying the accuracy of TBR predictions (and of the underlying nuclear data) by means of integral experiments based on neutron irradiation of BB mock-ups or subassemblies. The few available studies are not for US BB materials and designs. Integral experiments performed at the Fusion Neutronics Source facility of the Japan Atomic Energy Agency and at the Frascati Neutron Generator have reported that predictions of the tritium production rate agreed with the experimental measurement within an uncertainty ranging between 5% and 20% depending on the BB concepts and materials.

A.2.2 Current Production

The US currently produces tritium for national security applications through the irradiation of Tritium-Producing Burnable Absorber Rods (TPBARs), which consist of a $LiAlO_2$ ceramic rod with gettering materials and other layers to capture the produced tritium. These rods are irradiated in a Tennessee Valley Authority (TVA) power-generating reactor before the tritium is extracted for use at the Savannah River Site. Nuclear data needs for the prediction of tritium production within TPBARs and projections of tritium inventories in reactor coolant systems were presented by Richard Pagh (richard.pagh@pnnl.gov). Specifically, the tritium program data needs that were presented involve reducing uncertainty in Li, B, Be, $^{2}H, andGdcrosssections.The^{7}$Li(n,n'$\alpha$)T and ^{6}Li(n,$\alpha$)T reactions are the main tritium-producing reactions. The ^{7}Li(n,n'α)d reaction also contains substantial variations. Within the reactor environment are also other reactions of interest, such as reactions on Be. Elements B and Gd are neutron poisons for the reactor environment, and therefore, reduced uncertainty for reactions on these elements would be beneficial, as well. It was also identified that reactor benchmarks are needed that include high levels of burnable absorbers integrated in fuel and insert components to provide comparisons with commercial nuclear fuel vendor computer codes.

A.2.3 Potential Future Production

The US Tritium Modernization Program production method is an efficient mechanism to generate tritium, but other potential methods also exist, including accelerator methods and the use of advanced reactors that may provide a source of tritium for fusion R&D needs. The materials PbLi and FLiBe are two promising fusion reactor BB materials for their use of Li for tritium production. Although this method presents an opportunity for fusion systems, tritium production can become a nuisance for energy generation in advanced fission reactor setups such as molten salt reactors and flouride salt–cooled, high-temperature reactors. Understanding the production and uncertainty envelope for such a system would enable estimation of the extraction process or how necessary, and economical, it will be for these systems. Finally, accelerator tritium production was explored in the 1990s and determined to be too costly compared with reactor production methods. As technology advances, accelerator-driven opportunities may arise again.

A.2.4 Production in Tritium Breeding Blankets

Although tritium production in fission reactors may be necessary to supply a start-up inventory for early fusion reactors, the large quantity of tritium (55.6 kg/GW_{fus} year) required to sustain their continuous operation will necessitate the use of a tritium BB operating with a TBR >1. As noted previously, this is achieved in a lithium-bearing blanket in which tritium is produced via ^{6}Li(n,α)T and, to a lesser extent, ^{7}Li(n,n'α)T reactions. Because the former reaction has an increasing cross section with decreasing incident neutron energy and the latter has a relatively high energy threshold of 2.5 MeV, it is advantageous for all blanket concepts to enrich in ^{6}Li to some degree. Because a TBR >1 implies that every fusion neutron produces more than one tritium atom and parasitic absorption in structures is to be expected, some neutron multiplication is also required. Good neutron multipliers have high (n,2n) cross sections and low total absorption cross sections; Be and Pb have been identified as the best candidates. The tritium production, neutron multiplication, and other reaction cross sections for this short list of useful blanket materials (Li, Be, Pb) are therefore of paramount importance to the prediction of tritium breeding in the blanket.

There are three primary families of BB concepts. The first are based on liquid metals such as Li or PbLi eutectic. Solid ceramic breeders are also widely pursued; primary candidates include Li_4SiO_4 and Li_2TiO_3, which are typically paired with a solid Be or beryllide (e.g., $Be_{12}Ti$, $Be_{12}V$, or $Be_{12}Cr$) multiplier; the nonbreeding/multiplyling constituents of these materials (Si, Ti, O, V, Cr) are chosen to minimize neutron absorption that is detrimental to tritium breeding but also, importantly, to minimize neutron activation and the creation of long-lived (i.e., non-low-level) waste. Nuclear data for these elements are therefore also important to tritium breeding predictions. Molten salts (principally 2LiF/BeF_2, or FLiBe) are also considered, for which fluorine data will have an effect. All concepts may have a separate coolant, typically He or water, the nuclear characteristics of which are important to the function of the blanket.

Other nuclear data of importance to the blanket include the structural material constituents. Blanket concepts are likely to employ unique structural materials designed to minimize neutron activation and avoid creation of long-lived (non-low-level) radioactive waste. Primary near-term candidates are reduced-activation ferritic-martensitic (RAFM) steels such as F82H (Fe–8Cr–2W–0.2V–0.04Ta) and EUROFER-97 (Fe–9Cr–1W–0.2V–0.12Ta). Though likely less impactful to tritium breeding, certain impurity activation cross sections (e.g., Co, Nb, Mo) may be important to the waste categorization of these materials. Vanadium alloys such as V–4Cr–4Ti and SiC/SiC composites are also of interest for their very low activation characteristics. Tungsten, in addition to being a minor alloying element in RAFM steels, finds multiple other applications (e.g., as a plasma-facing surface, conducting shell to aid plasma stability, or as a component of shielding) in fusion reactors, and its absorption characteristics are therefore also of importance to the blanket.

A.2.5 Current R&D

Recent statistical analysis of TBR calculations due to nuclear data leveraged the TENDL-2017 and TENDL-2019 libraries for their structural materials' nuclear data needs largely because of the availability of evaluated means and covariance data for all isotopes, as well as sufficiently large sets of statistically consistent randomized nuclear data samples for almost all isotopes. An assessment of the quality of these data and the identification of potential gaps in which new differential experiments or predictive nuclear theory calculations would help reduce uncertainties is recommended. Additionally, particular emphasis should be placed on assessing the quality of data and uncertainties for tritium breeding materials, particularly the tritium-producing ^{6}Li(n,T)^{4}He, ^{7}Li(n,nT)^{4}He reactions and the ^{9}Be(n,2n)2^{4}He neutron multiplier. Also, the ^{10}B(n,T)2^{4}He plays an important role in the tritium accounting for the Tritium Modernization Program.

The ^{6}Li(n,T)^{4}He cross section below about 1 MeV is a neutron standard and has been evaluated extensively using large multichannel $\mathcal{R}$-matrix analyses up to 4 MeV and extended to 20 MeV using other methods. Evaluated uncertainties have been revised over the years based on the concern that they may be too small and not adequately embracing newer experimental data. In ENDF/B-VIII.0, the evaluation includes a covariance only up to 4 MeV incident neutron energy. Uncertainties are very small in the thermal region (below 1%), then climb to about 10% at 4 MeV. Although there are multiple measurements for reaction cross section, covering the energy range up to 20 MeV, experimental data for angular distributions are scarcer.

Fewer experimental datasets with larger discrepancies among each other are available for ^{7}Li, ^{9}Be, and ^{10}B compared with ^{6}Li. Both ^{7}Li and ^{10}B allow for several pathways for producing tritium: through the breakup of excited states after inelastic scattering and the intermediate formation of the ^{5}He and ^{8}Be metastable states, respectively. For ^{7}Li, the ENDF/B-VIII.0 evaluation includes a total tritium production cross section with associated uncertainty. Covariance data are only given for incident neutrons above 12.5 MeV. The uncertainty is around 2% near 14 MeV, increasing to 40% above 16 MeV.

In addition to *R*-matrix analyses, first-principle (or *ab initio*) informed evaluations are now also becoming possible for neutron reactions with light nuclei enabled by the deployment of advanced computing architectures that utilize graphics processing units (GPUs) as accelerators. These evaluations rely on microscopic methods capable of accurately describing the reaction dynamics of light nuclei starting from their constituent protons and neutrons. The sole inputs are high-quality interactions among the nucleons. *Ab initio* calculations are very computationally intensive: they typically require multiple runs that take up a significant part of high-performance computing systems (and can scale up to utilizing the entire machine). Although more costly than phenomenological analyses, they have the advantage of being less reliant on experimental data and, thus, better suited to dealing with absent or incomplete data. They also allow researchers to correlate different reaction observables (e.g., cross sections and product distributions) as well as reactions for different systems (e.g., neutron-induced reaction on ^{6}Li and ^{7}Li), thus offering a robust approach to obtaining well-evaluated uncertainties and covariance data. As an example, an accurate *ab initio* informed evaluation, including uncertainty quantification, of the ^{6}Li(n,T)^{4}He neutron standard reaction and the angular distribution of its products was recently carried out at Lawrence Livermore National Laboratory. The development of predictive evaluation methods that leverage advanced simulation and computing will have a significant effect beyond fusion energy applications and is a shared interest of the NNSA Office of Advanced Simulation and Computing and Institutional Research and Development.

A challenge in performing complete coincident measurements and in evaluating data for neutron reactions with Li, Be, and B is the presence of multiparticle reaction outcomes already at fairly low energies. In particular, the treatment of such multiparticle breakup remains a challenge for both phenomenological *R*-matrix and more microscopically grounded theoretical models used to perform evaluations.

Some measurements have been made of the breakup reactions in Li using fast neutrons generated by inertial confinement fusion at the OMEGA laser facility at the University of Rochester Laboratory for Laser Energetics. As noted above, these reactions are important to the operation of tritium breeding blankets. Assessments of existing experimental data for the ^{7}Li(n,nT)^{4}He reaction show large disagreements below the second inelastic excited state and reveal a lack of any experimental data below 30° for 14 MeV neutrons. New measurements at OMEGA showed generally good agreement with earlier data for both ^{6}Li and ^{7}Li but significantly higher (n,2n) cross sections at near-zero emission angle; more measurements are needed and have been proposed.

One avenue for developing an understanding for tritium production mechanisms for both advanced reactors and fusion breeder blankets is the use of D-T generators, which provide 14 MeV neutrons. SHINE's Fusion Linear Accelerator for Radiation Effects (FLARE) Facility contains a high-flux D-T generator (5×10^{13} n/s). The facility can irradiate material from 8 to 192 h continuously in their irradiation cavity, which surrounds the source. This setup can be used to study a variety of tritium breeder blanket materials (Li, PbLi, FliBe) for small- to large-scale design experiments. The source could be potentially leveraged as a future benchmark experiment for fusion reactor efforts. At present, the facility can be used for 14 MeV cross section measurements of interest.

Benchmarks are essential to provide validation that analytical methods adequately represent reality for a given application: they are integrated tests of the evaluated nuclear data, nuclear data processing codes, and transport codes. Benchmarks are well-characterized experiments in which all experimental uncertainties are carefully evaluated and bias and uncertainties due to model simplifications, geometry simplifications, room return, material impurities, and more are meticulously accounted for. Integral benchmarks test multiple data (isotopes, reactions, energies) at once, but they may also be designed to be particularly sensitive to one piece of data. Examples of integral benchmarks are critical assemblies, subcritical assemblies, reactor operation data, shielding experiments, and postirradiation examination.

Currently, there are no (sanctioned) integral benchmarks for fusion breeder blankets. Some benchmarks with ^{6}Li exist for energies corresponding to the neutron spectrum from fission. There are no experiments for the neutron spectrum of interest for fusion energy applications. An ideal initial benchmark for testing tritium production rates would be postirradiation examination, or PIE. In this type of experiment, production targets or samples are irradiated in a known neutron flux (e.g., from a reactor). After irradiation, the samples are taken to a hot cell facility for disassembly and characterization. The benchmark would be given by a combination of irradiation history and before-and-after compositions of the targets. Improving on this, one could also include in the benchmark information about the neutron source and sample geometries, as well as high-fidelity modeling of the irradiation history. Modern PIE experiments have been conducted by Pacific Northwest National Laboratory (not published as benchmarks, e.g., the TMIST experiments at the Advanced Test Reactor at Idaho National Laboratory). Access to existing relevant integral and diagnostic data at national laboratories and other US programs would help define and narrow down the best integral benchmarks for tritium production. Differential or integral experiments for tritium production could be pursued using the neutrons sources of the FLARE facility at SHINE Technologies, the OMEGA laser facility at the Laboratory for Laser Energetics, and the National Ignition Facility (NIF).

A.2.6 Recommendations for Nuclear Data to Address Toward T-Production for Fusion

Following this session, the community made the following recommendations:

- A scoping study is recommended to identify and narrow down the specific nuclear data inventory, including required accuracies and priorities, for breeder, multiplier, and structural materials used in US fusion reactor and breeding blanket designs. This study will require (1) a survey of existing studies on the nuclear data uncertainties in calculations of the achievable TBRs and their comparison with available benchmark tests in Europe and Japan and (2) new, complementary sensitivity studies (with full propagation of nuclear data uncertainties) of TBRs for blanket materials used in US magnetic fusion energy and inertial fusion energy fusion reactor concepts.
- A second scoping study is recommended to assess the status of differential measurements, predictive simulations, and phenomenological analyses for tritium production–relevant nuclear data and their ability to fill gaps in evaluated means and covariances for cross sections, angular distributions, and exit-channel product information, particularly in the intermediate and fast neutron energy regime. Such assessment will help identify priorities for new measurements and calculations to improve nuclear data libraries.
- A third scoping study is recommended to build a path toward integral benchmarks for neutron energies and fluxes relevant for tritium production in US blanket designs. A survey of existing relevant integral and diagnostic data at national laboratories and other US programs is needed to help define and narrow down the best integral experiments; initial integral experiments for US blanket subassemblies by leveraging current facilities that can offer high fusion neutron fluxes should be conducted to provide guidance for the development of fusion-integral benchmarks.
- A funding mechanism to facilitate and stimulate the exchange of information and collaboration among the fusion energy, defense, and nuclear data communities will be essential to accelerate the path to tritium self-sufficiency while also supporting commercial tritium production for maintaining the US nuclear weapons stockpile.
- Access to advanced high-performance computing architectures and collaborative funding mechanisms to strengthen the quality and support the continuous development of software used across the nuclear data pipeline will be essential to assess the viability of future commercial power plants and continue to support the US nuclear deterrence mission.

A.3 FES: MATERIAL DAMAGE

A.3.1 FES Perspective of Material Damage (Guinevere Shaw, DOE-SC/FES)

Speaker: Guinevere Shaw (US Department of Energy Fusion Energy Sciences)

Guinevere Shaw, the program manager for the Materials and Fusion Nuclear Science program under DOE Fusion Energy Sciences (FES), gave a presentation highlighting the FES program vision, priorities, and current thoughts on the challenges with respect to materials for fusion energy systems. Recent community prioritization activities have emphasized the need to urgently expand efforts in the area of materials development. Materials challenges include plasma–material interactions (sputtering, tritium implantation, high heat fluxes), material degradation (structural stability, reduced activation materials, corrosive environments), and the ability to harness fusion energy (efficiently extracting tritium, instabilities). One aspect that was highlighted in Shaw's talk was that there is very limited data and understanding of material degradation in the regime of high dose and high gas production from transmutation. Computational modeling will be important as a complement to experimental studies but will need to contend with challenges related to multiscale time integration across rare dynamics and modeling multicomponent alloys with transmutant impurities. Lastly, Shaw drew attention to the fact that nuclear data uncertainties above 10 MeV for some elements will be important.

A.3.2 Nuclear Data Applications to Integrated Modelling of Materials Damage

Speaker: Mark Gilbert (UK Atomic Energy Authority)

Mark Gilbert gave a talk discussing recent code advancements at the UK Atomic Energy Authority (UKAEA), namely the development of the SPECTRA-PKA [3] code, which provides users a way to directly obtain primary knock-on atom (PKA) distributions (which are normally intermediate products in the calculation of displacements per atom [dpa] and are not visible to a user). The PKA distributions allow the community to move beyond basic models of dpa (e.g., NRT-dpa [4]) toward more realistic atomistic simulation. Mark demonstrated how the PKA distributions could be randomly sampled to generate distributions of displacements within a 3D volume over time, allowing one to visually see where displacement cascades could potentially overlap. Going further, some initial efforts were made toward coupling with a binary collision approximation (BCA) code to do simplistic atomistic modeling using PKA energies sampled from distributions produced by SPECTRA-PKA. Overall, the work shows one of the first efforts toward bridging scales—in this case, nuclear physics with atomistic scale—and discussion centered around the need to go further to be able to understand mesoscale and ultimately macroscale behavior.

A.3.3 Status of Complete Neutron-Induced Displacement Damage Cross Section Data

Speaker: Dieter Leichtle (Karlsruhe Institute of Technology)

Dieter Leichtle described work at Karlsruhe Institute of Technology (KIT) on the production of displacement cross sections based on the arc-dpa [5] formalism along with uncertainty propagation. The arc-dpa parameters for this work were based on a combination of experimental data and systematics. Because the "standard" data processing pipelines do not handle arc-dpa, the KIT team had to rely on a combination of NJOY [6], PREPRO, and a newer code called BEKED to produce arc-dpa cross sections. This work was done for 78 elements ranging from Be up to Bi based on source data from the JEFF 4T2.2 test library. Dieter noted that unphysical jumps in cross sections were observed for many elements. Displacement cross sections were extended out to 200 MeV via bridging data from multiple libraries. The BEKED code was also used to produce random files from covariance data based on a total Monte Carlo approach. Correlations between neutron energies were shown to be dominated by the damage model (particularly the threshold displacement energy).

A.3.4 Fast Neutron Irradiation of High Temperature Superconducting Magnets

Speaker: Lee Bernstein (University of California, Berkeley)

Lee Bernstein presented results from an experimental campaign using the 88 in. cyclotron at Lawrence Berkeley National Laboratory to produce neutrons via thick-target deuteron breakup reactions (40 MeV deuterons) to irradiate rare-earth barium copper oxide (ReBCO) and bismuth strontium calcium copper oxide (BSCCO). The neutron source was quantified using time-of-flight and activation techniques. One nice feature of the experiment was the ability to obtain simultaneous measurements from the spectral variation as a function of angle. With the ReBCO tapes irradiated, plans have been made to assay changes to critical current, critical temperature, and other key parameters. Prof. Bernstein highlighted that future campaigns could produce significant gas production, displacements, and secondary particle production, and he sought input from the fusion community on what experiments would be valuable that could be conducted using the available capabilities.

A.3.5 Radiation Damage to Electronics at the NIF

Speaker: Hesham Khater (Lawrence Livermore National Laboratory)

Hesham Khater gave a presentation describing the effect of radiation damage on electronics at the National Ignition Facility. During operation, exposure of electronic equipment to a high level of neutron and photon radiation can result in permanent damage to electronics, affecting the experimentalist's ability to collect data. Permanent damage is caused by total ionizing dose (dominated by higher energy neutrons) but is generally easier to shield against due to radiation directionality. Nevertheless, displacement damage caused by neutrons at all energies can produce hot pixels in cameras. Khater stressed that accurate prediction of displacement damage and nonionizing energy loss is essential to establish a relation between the expected radiation environment and whether critical electronic components will survive. He also discussed how calculations are currently based on an equivalent fluence method from the ASTM E722-19 standard, which is based on decades-old data, so there is a question of how much the results would change if newer data were used.

A.3.6 Efforts to Improve the Accuracy of Calculated Displacement Damage

Speaker: Paul Romano (Argonne National Laboratory) on behalf of Shengli Chen (Sun-Yat Sen University)

Paul Romano presented a collection of work on behalf of Shengli Chen, who has done extensive work on understanding and improving displacement cross section data. Chen's talk included three components. (1) An overview was given of a UQ study on damage in a reactor pressure vessel [7], where it was shown that the uncertainty due to the neutron flux and displacement cross section was about 12%. With an assumed 20% uncertainty on the threshold displacement energy (TDE), the uncertainty rose to 23%, whereas a 5% assumed uncertainty on the TDE resulted in a much smaller increase in overall uncertainty. This result leads to the question of what is more important—if the cross sections or fluxes are well known, the uncertainty on the TDE may very well become important. However, if the uncertainty on the flux or cross sections is large, the uncertainty in the TDE may not matter. Further studies were recommended to understand uncertainties in fusion systems specifically. (2) Various problems were identified with specific evaluations regarding the recoil distributions present in ENDF files [8, 9]. Overall, the takeaway message was that often, the recoil distributions in ENDF files are not of very high quality, and this issue has manifested itself in very poorly predicted displacement cross sections (either under- or overestimated). Surprisingly, an easy fix to obtain reasonable displacement cross sections is to remove the recoil distribution from an ENDF evaluation entirely, which forces NJOY to rely on two-body kinematics to estimate a recoil energy. Chen and Romano recommended that the data community implement better sanity checks on evaluations to ensure that unphysical recoil distributions do not end up in evaluations before they are released. (3) Efforts were described wherein past experimental measurements of damage (measuring changes in electrical resistivity, which relates to the number of Frenkel pairs produced) were used to find optimal parameters for the arc-dpa damage model. This work was done for both neutron irradiation experiments and d/p/α irradiation experiments. Different optimal parameters were found depending on which set of experiments were included, which raises the question of which parameters ought to be adopted.

A.3.7 Discussion

This session and the others that preceded it highlighted a variety of needs in the community, covering measurement, evaluation, processing codes, and verification and validation. Given the wide set of needs and limited resources in the community, there was ample discussion on a desire to comprehensively identify the needs, assess how much effort addressing each would take (and if relevant capabilities—experimental, computational, or otherwise—are already available), and, based on this information, come up with a set of priorities. In general, the need to qualify materials at high dpa/high He production requires facilities that do not exist today, but many other needs could be addressed given already-existing facilities at national laboratories and universities. Several participants stressed the need to ensure that the "lines of communication" between the nuclear data and fusion energy communities remain open, building off of 2023 OSTP meeting and continuing with this year's WANDA sessions focused on FES. One industry participant commented that there needs to be better mechanisms for reporting issues with nuclear data back to the data community itself (e.g., through publicly accessible, open source repositories).

A.4 ISOTOPES AND TARGETRY FOR NUCLEAR DATA

This session was focused on isotope and targetry needs and capabilities. Thanos Stamatopoulos and Sean Kuvin from Los Alamos National Laboratory gave talks focused on target needs with a focus on radioactive and highly enriched stable targets and the importance of adequate target characterization. Samantha Labb from Lawrence Livermore National Laboratory provided a talk focused on capabilities and application specific needs for inertial confinement fusion at the National Ignition Facility. Claus Müller-Gatermann from Argonne National Laboratory, Mike Zach from Oak Ridge National Laboratory, and Khachatur Manuykan from University of Notre Dame presented talks covering novel target fabrication capabilities at their respective facilities. The discussion in this session was focused on the needs of experimental data community and what aspects of targets most significant, as well as how these needs can best be met. There was also significant discussion around the need for workforce development for target fabrication and capabilities to ensure this knowledge is not lost as experienced target makers retire. A detailed summary of the topics covered in each talk is provided below.

A.4.1 Wanted: Tiny Radioactive Samples for Neutron Transmission Measurements with DICER at LANSCE

Speaker: Thanos Stamatopoulos (Los Alamos National Laboratory)

This talk outlined the details of sample preparation and analysis at Los Alamos National Laboratory for neutron transmission measurements using DICER. Dr. Stamatopoulos described the specific requirements for the targets, which include a variety of formats such as powder, liquid, and metallic, with precise dimensions (0.1 mm or 1 mm diameter and 1.5 cm length). The preparation of such targets includes encapsulating samples in a capillary tube, sealing them with a plug, and placing them in a canister. Liquid radioactive samples are dispensed in W canisters and metallic samples in Al screw-down canisters. Replacing H in the samples with deuterated compounds minimizes neutron absorption and enhances their neutron transmission properties. Special equipment developments, such as a new 0.1 mm collimator and inkjet printing for small-diameter samples, were discussed, highlighting advancements in handling and analyzing tiny radioactive samples for precise measurements. Additionally, Dr. Stamatopoulos covered the collaboration between Los Alamos Neutron Science Center (LANSCE) and IPF in fabricating radioactive samples, specifically citing the successful case of ^{88}Zr production, and outlined future plans for studying various nuclides with different half-lives.

Nuclide	Half-life
^{88}Y	106.6 days
^{107}Pd	6.5 10^{6} years
^{134}Cs	2.065 years
^{147}Pm	2.62 years
^{152}Eu	13.52 years
^{155}Eu	4.75 years
^{153}Gd	240.4 days
^{163}Ho	4570 years
^{170}Tm	128.6 days
^{185}W	75.1 days
^{186}Re	3.72 days
^{192}Ir	73.8 days
^{193}Pt	50 years

Nuclide	Half-life
^{3}H	12.3 years
^{171}Tm	1.92 years
^{151}Sm	90 years
^{2}H	stable
^{133}Cs	stable
^{40}Ar	stable

Figure 3. Radioactive isotope targets needed for the future.

A.4.2 Target Needs for Neutron-Induced Charged Particle Reactions at LANSCE

Speaker: Sean Kuvin (Los Alamos National Laboratory)

Dr. Kuvin discussed the requirements and methodologies for neutron-induced charged-particle reaction studies at LANSCE. The presentation focused on the production and characterization of isotopes—specifically, thin, uniformly deposited targets made from radioactive or rare isotopes, which pose challenges in fabrication because of complex chemistry and deposition methods. These targets must be relatively thin (typically 1 μg/cm^2 to 1 mg/cm^2) to facilitate accurate (n,z) measurements. This requires precision in the uniformity of deposition across the target area, which is particularly challenging when working with radioactive or rare isotopes. Techniques such as thermal evaporation, printing, and electrodeposition are explored to achieve the desired purity and mass consistency. Collaboration was highlighted as a crucial element, involving experts from Los Alamos National Laboratory, University of Notre Dame, and Michigan State University, among others. These collaborations aim to leverage diverse expertise to refine target fabrication processes and enhance the characterization of targets. The presentation also included details about specific isotopes (e.g., ^{56}Ni) and discussed the importance of integrating advanced fabrication and chemical separation technologies to maintain the integrity and usefulness of the targets in experimental setups. Dr. Kuvin also underscored the ongoing need to advance target fabrication technology and chemistry to keep pace with the evolving demands of nuclear physics research. He emphasized the importance of interdisciplinary training and collaboration to enhance the capabilities of neutron-induced nuclear reaction studies.

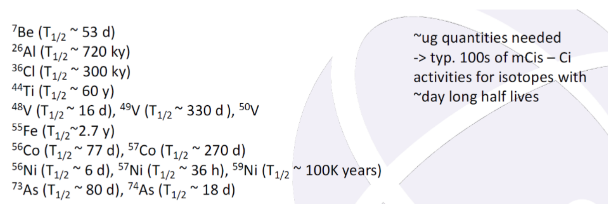

Figure 4. An incomplete list of rare/radioactive samples of interest to be fabricated into thin targets for (n,z) measurements.

A.4.3 Development of Radiochemical Techniques for Doping NIF Capsules with Radioactive Material

Speaker: Samantha Labb (Lawrence Livermore National Laboratory)

This presentation detailed the sophisticated methodologies and challenges of doping National Ignition Facility (NIF) capsules with radioactive/rare isotopic material for neutron capture cross section measurements. Dr. Labb emphasized the development and refinement of platforms for measuring (n,2n) cross sections on radioactive species using minute amounts of dopant thanks to the large neutron flux at NIF.

The work included innovative solutions for precise capsule doping, utilizing systems like the Apparatus for NIF-Doping Automated Robotic Injection System for Targets (ANDARIST) and Vacuum Optimized Radionuclide Capsule Administer (VORCAN) alongside stringent purity and isotopic quality controls to ensure accurate measurement outcomes. The platform developed for measuring ^{88}Y(n,2n)^{87}Y at 14 MeV involves preparing and handling radionuclides, ensuring they are free from impurities that could affect the measurements. A significant challenge in doping is maintaining isotopic purity and solution cleanliness to prevent clogging the small fill holes of the capsules (10 μm diameter). The timeline from the development of the radionuclide cocktail to the actual shot at NIF spans over a year, requiring precise coordination of production, purification, and doping processes to meet the shot schedule.

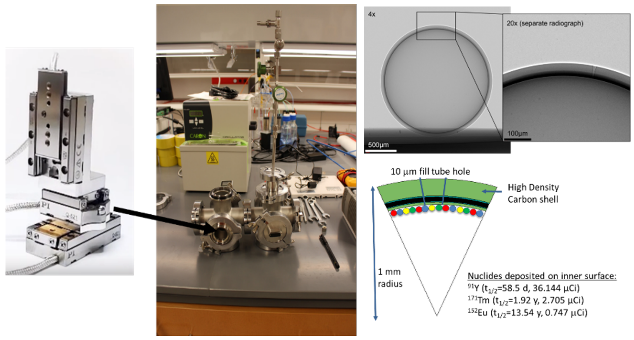

Figure 5. VORCAN setup and spherical doped capsule targets.

A.4.4 Tritium-Doped Titanium Foil Production at CATS

Speaker: Claus Müller-Gatermann (Argonne National Laboratory)

Dr. Müller-Gatermann presented the efforts at the Center for Accelerator Target Science to develop tritium Ti foil for use in nuclear physics experiments—specifically for (t,p) reactions and as targets for radioactive triton beams. Tritiated Ti foils have been produced successfully using a small tube furnace setup at Argonne National Laboratory for hydrogenation tests with deuterium as a surrogate before moving on to tritium. Titanium hydride (TiH_x) is formed by heating Ti in an atmosphere above 300°C, reaching a maximum H content of $x = 2.0$. A challenge for producing such targets is that the foils become brittle after preparation. This significantly complicates the handling and mounting procedures of targets. Characterization methods, including x-ray diffraction and ion beam scattering, were employed to analyze the material properties and loading factors of these foils. The project faces challenges such as the brittleness of tritiated Ti and contamination risks but offers promising avenues for advancements in handling tritium in nuclear target applications. Dr. Müller-Gatermann mentioned the ongoing development of tritiated polyethylene and the potential for future experiments at Argonne National Laboratory, Facility for Rare Isotope Beams, and CERN requiring low-Z beam targets. Reduction of dead volume and recycling are considered important future strategies to improve the efficiency and safety of tritium target production.

Figure 6. A tube furnace with a manifold for pumping, purging, and H source is needed. Test foils with deuterium as a surrogate.

A.4.5 Development of Spherical Metal Powder Targets

Speaker: Mike Zach (Oak Ridge National Laboratory)

Dr. Zach introduced the creation and applications of spherical metal powders for nuclear data experiments. These powders are designed to optimize the handling and deployment of isotopes in various nuclear research applications, including 3D printing, novel porous targets, and inverted target designs. Utilizing ultrasonic atomization and induction melting, the process focuses on producing powders with controlled properties such as flow and clumping, which are crucial for successful application in 3D printing and other uses. The powders can be used to create porous structures that facilitate better handling and use in nuclear experiments. The spherical nature of the powders allows for more precise placement and dispensing, treated similarly to liquids or gases, which is a significant improvement over traditional powder handling. Dr. Zach discussed ongoing development and potential future enhancements, including refining the spherical powder properties and expanding their applications in isotope production and other areas of nuclear science.

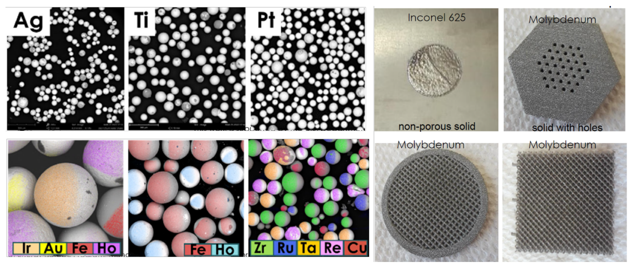

Figure 7. Spherical powders and powders enable new 3D options for making targets.

A.4.6 Emerging Combustion Synthesis Methods to Prepare Thin Targets for Nuclear Science Research

Speaker: Khachatur Manukyan (University of Notre Dame)

This talk was centered on the solution combustion synthesis (SCS) of actinides. This innovative SCS method uses metal nitrates and organic compounds to rapidly produce nanoscale materials such as oxides, metals, and alloys in a bulk powder form. These reactions are exothermic, releasing sufficient heat to sustain themselves, thereby minimizing or eliminating the need for external heating sources. The method enables the preparation of isotopically pure and uniformly deposited targets on various substrates through spin-coating, spraying, and inkjet printing. These targets are adjustable in thickness and have undergone rigorous analysis through alpha-particle emission spectroscopy, x-ray fluorescence, x-ray photoelectron spectroscopy, and high-resolution transmission electron microscopy, demonstrating high stability and durability postirradiation with charged particles and neutron beams. The adaptability of SCS in fabricating high-quality targets for diverse nuclear applications was emphasized, highlighting its efficacy and precise control over material properties. The group at University of Notre Dame has also forged strong collaborations with national laboratories, particularly in preparing targets for Los Alamos National Laboratory.

Dr. Manukyan stressed the importance of training the next generation of scientists skilled in using these advanced techniques and methodologies. The students gain hands-on experience in various experimental techniques related to actinide chemistry, target tests, detectors, and nuclear reaction measurements. Two graduate students, Jordan Roach and Stefania Dede, have successfully defended their PhD theses. After completing his degree, Jordan Roach took up a postdoctoral research position at Oak Ridge National Laboratory's Nuclear Nonproliferation Division Materials and Chemistry Group, where he focuses on materials relevant to the initial stages of the nuclear fuel cycle and is enhancing SCS capabilities for nuclear forensics research and development. Stefania Dede now works as a postdoctoral researcher with the Low-Temperature Detectors (LTD) team at Los Alamos National Laboratory, where she designs sample preparation procedures for microcalorimeter detectors and is involved in preparing targets for fission fragment experiments using the SPIDER detection setup at LANSCE.

A.4.7 Isotopic Target Needs Survey Results

As a supplemental source of information to assess community needs and as context for the discussion, an isotope target needs survey was sent out to the attendees of WANDA 2024 in advance of the workshop. The

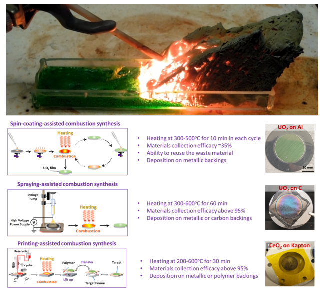

Figure 8. SCS of actinide targets.

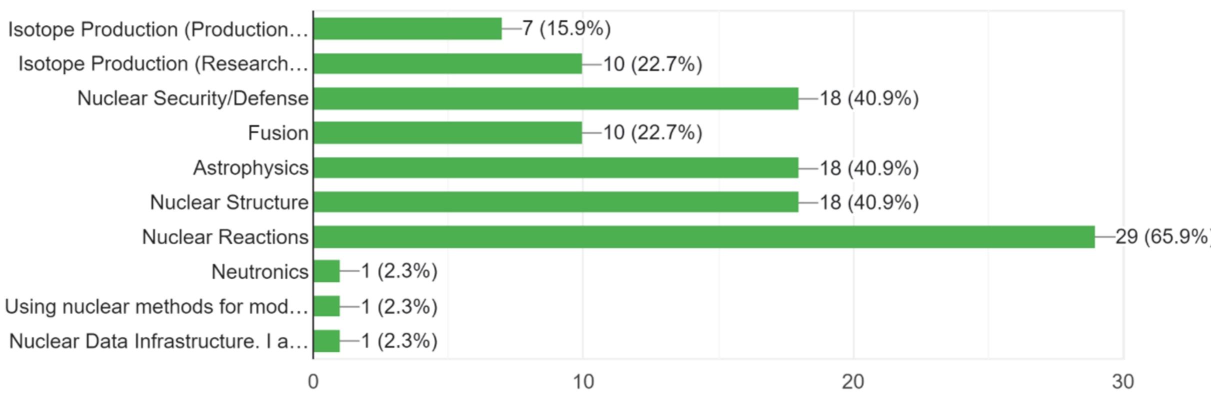

Figure 9. Areas of research reported by the respondents (44 responses).

survey responses are detailed below.

Respondent Data There were 44 unique responses to the survey (36 professional-level scientists, 7 postdoctoral researchers, 1 graduate student). The respondents worked primarily at government laboratories (28), followed by academia (13) and limited industry partners (3). Respondents were asked to report their area of research; there was a fair representation of Isotope Program, Nuclear Defense, and Nuclear Physics needs (Figure 9).

Target Needs Data A series of questions were postulated to identify target material and material form needs. The respondents utilize a broad range of thin films, thick foils, liquid or frozen targets, and gas targets. A majority (71.4%) reported that they needed isotopically enriched materials/targets, and more than half (52.4%) reported using radioactive targets/materials. A majority of respondents have specific isotopic purity tolerances (Table 1). From the respondent data, it is evident that a range of enrichments will find use within the community.

Table 1. Isotopic purity tolerances (43 responses)

Isotopic Enrichment	Respondents
No Requirement	14
80%+	16
90%+	15
95% +	11
99% +	9

Respondents were asked to provide feedback on target materials and forms they were struggling to source; these needs are captured in Table 2. An additional constraint in the production, transportation, and handling of target is air sensitivity. A majority of respondents (58.5%) reported having specific target needs necessitating vacuum or an inert atmosphere; responses included were Li, Na, Mg, K, Ca, Bi, ^{133}Cs, rare earth metals, alkaline/alkaline earth (nonspecific), and that oxidation/oxides are a problem for background effects.

Table 2. Isotope materials and target needs (21 responses)

Need	Responses
Enriched Isotopic Materials	^{6}Li, ^{10}Be, ^{13,14}C, ^{17}O, ^{26}Al, ^{39}K, ^{52}Cr, ^{59}Fe, ^{88}Y, ^{115}Sn ^{132}Ba, ^{144}Ce/^{144}Pr, ^{151}Sm, $^{152,\,160}$Gd, ^{180}Hf, ^{235}U, ^{254}Cf
Enriched isotope (nonspecific)	Actinides (multiple requests)
Target form	Crystal bar Ti and Zr
Target form	Targets from all even Sn isotopes
Target form	Deuterated and tritiated materials (multiple requests)
Target form	Targets of ^{13}C
Target form	Thin films of actinides (multiple requests)
Target form	Thin ^{252}Cf films on thin backing/10 $\mu g/cm^3$ C (multiple requests)
Target form	^{32}Si as a solid target

A final question was asked for any unmet needs beyond the scope of the survey; these are listed below.

Responses

1. Need targets relevant to tritium breeding reactions
2. Targets that are homogeneous
3. Fluorine-free target material and Ta or W beamstop backings. This has been a really long-standing target problem. High-temperature heating can reduce the F by about an order of magnitude, but even greater reduction is highly desired. This is mainly for (p,/*gamma*) measurements at low energy with high beam intensity where 6 MeV gamma rays are produced by the ^{19}F(p,$\alpha\gamma$) reaction.
4. Need the ability to handle Pu: make thin foils (on backings) and put them in chambers
5. Need samples that can be activated beyond the current allowable limits

A.5 UNCERTAINTY QUANTIFICATION

The uncertainty quantification (UQ) session was organized, curated, and led by Nathan Gibson (Los Alamos National Laboratory [LANL]), Denise Neudecker (LANL), Robert Casperson (Lawrence Livermore National Laboratory [LLNL]), and Ugur Mertyurek (Oak Ridge National Laboratory [ORNL]). The session was designed to delineate the needs for two different communities that interact with nuclear data (ND) UQ data: evaluators who improve and expand the data and users who use the data to predict uncertainty in applications. The session was broken into two different parts that focused on these communities.

A.5.1 WANDA 2024: Uncertainty Quantification

Speaker: Nathan Gibson (LANL)

To open the UQ session, some of the history of UQ discussions in the past were outlined, and the objectives of the session were laid out based on the feedback of the most recent UQ discussions preceding the WANDA 2024 meeting. These objectives were defined as the following:

1. Medium-fidelity covariances
2. Quality assurance of covariances
3. Improved experimental UQ
4. Covariance and UQ training for users
5. Adjustment tools for general users

Several discussion topics were also identified that the session should focus on:

- What impact can UQ have on our applications?
- What additional needs do we have to make UQ more mainstream?
- What would investments in the top priorities look like?
- What would investments in other areas look like?
- How do we work together as a community in this area?

It was also emphasized that a great deal of UQ work is already ongoing. This work includes quality assurance in the Cross Section Evaluation Working Group (CSEWG) during ENDF/B releases, the templates of experimental uncertainties [10], and UQ-based workflows for the customers of LANL, ORNL, and LLNL. It was especially emphasized that although ongoing work from various program sponsors demonstrates interest from application communities and that recent successes demonstrate the ND community's ability to make progress, significant concerted efforts are missing to move the status quo and increase the impact of those efforts.

A.5.2 Resolving ^{35}Cl Nuclear Data Uncertainties

Speaker: Tommy Cisneros (Terrapower)

Terrapower's Molten Chloride Reactor Experiment (MCRE) is a chloride salt fuel, fast–neutron spectrum molten salt reactor. MCRE is fueled with a NaCl–UCl_3 eutectic fuel salt with natural Cl. Preliminary analysis shows that reactivity in MCRE may change by 2,200 pcm depending on which ^{35}Cl evaluation is used—this sensitivity is driven primarily by the ^{35}Cl(n,p) cross section.

The evaluated cross section for the ^{35}Cl(n,p) reaction has changed significantly between ENDF/B-VII.1 and ENDF/B-VIII.0. Following the ENDF/B-VIII.0 release, several measurements were made by Batchelder et al. [11], Kuvin et al. [12], and Warren et al. [13] which were largely in agreement with each other and discrepant with the evaluated cross section in ENDF/B-VIII.0. It was also noted that the ENDF/B-VIII.0 library does not have uncertainty information above 1.2 MeV, where sensitivity to the MCRE neutron multiplication rate is very high.

With the addition of new measurements from LANL; University of California, Berkeley; and Ohio University, a new evaluation was able to be made for Terrapower that showed improved agreement with the measured data. This new evaluation will be submitted for future releases of the ENDF/B library.

A.5.3 Uncertainty Analysis in Nuclear Forensics

Speaker: Corey Keith (LANL)

Nuclear forensics mainly seeks the answer to the following questions:

- Whose was it?
- What was it?
- Are there more?

Nuclear forensics seeks to answer those questions using the best nuclear data available. ND from many nuclides are necessary to properly model applications for nuclear forensics, including fission products, short-lived actinides, activation products, and long-lived actinides.

To answer these questions, researchers rely on nuclear debris "signatures" (e.g., fission products) and associated nuclear data. However, these forensic signatures often provide correlated information that requires careful uncertainty treatment. Even for an artificially simple problem (e.g., differentiating between two nuclear fuels with three fission product measurements), researchers can observe the strong effect that "missing" ND uncertainties have on the analysis. Realistic nuclear forensic scenarios are complicated, and researchers often do not realize the effect without "filling in" the uncertainty gaps. A potential solution is to include low- to medium-fidelity uncertainties, enabling sensitivity studies to determine higher-priority evaluations.

A.5.4 The BAND Software Framework

Speaker: Kyle Godbey (Facility for Rare Isotope Beams)

All physical models, whether phenomenological or microscopic, are imperfect descriptions of reality. The goal of UQ, then, is to rigorously quantify those imperfections in a principled way to ensure valid interpretations of existing data and trustworthy predictions of unobserved events. Just as physicists construct models to simulate physical processes, statisticians carefully consider the possible sources of uncertainty and construct a statistical model that serves to connect the physical model to observed data. Some examples of those considerations include defining the assumed distribution obeyed by a random process, prior assumptions on uncertainties and correlations within the data, and even the underlying deficiency of the physical model. This last part is often overlooked and is important to quantify the missing ability of the physical model to explain and predict the phenomena of interest [14]. Another important consideration that is becoming more pressing in the modern data science landscape is to ensure that any UQ study or outcome is both trustworthy and reproducible, particularly when machine learning methods are integrated into the UQ pipeline. To that end, the community should take care to embrace repeatable pipelines [15], preserve model posteriors and predictions [16], and, where appropriate, distribute predictions and evaluations with full uncertainties and metadata detailing the methods and assumptions used to generate the data [17]. One way to streamline this process would be to, upon clearly determining the community needs in this space, actively engage with open-source software frameworks [18] to ensure those community needs are being met broadly. Although this requires significant investment in technology and personnel, the resulting modernized pipeline serves to enhance overall operational efficiency and aid the delivery of trustworthy nuclear data for forefront science and vital applications.

A.5.5 Shortcomings in EXFOR Hindering Experimental UQ and AI/ML Analysis

Speaker: Boris Pritychenko (Brookhaven National Laboratory)

Experimental Nuclear Reaction Data, or the EXFOR library, is more than 50–70 years old, and its compilation rules have evolved over the years. The EXFOR compilation philosophy is to compile data as they were published (in consultation with authors) unless obvious errors are found, and such nuclear reaction data contain outliers, discrepancies, and limited description or lack of uncertainties. The following picture would emerge if the EXFOR library was analyzed for uncertainties:

- 48% of EXFOR entries contain uncertainties without any description (DATA-ERR)
- 19.9% of EXFOR entries contain total uncertainties (ERR-T)
- 14.1% of EXFOR entries contain statistical uncertainties (ERR-S)
- 2.1% of EXFOR entries contain systematic uncertainties (ERR-SYS)
- 15.9% of EXFOR entries contain no uncertainties
- Finally, only 0.525% of EXFOR entries include covariances

EXFOR compilation and maintenance was not systematic and represented an issue for nuclear data evaluators and application developers. The researchers hope the above-mentioned EXFOR shortcomings will be addressed in the future EXFOR modernization project and Working Party on International Nuclear Data Evaluation Co-operation (WPEC) SubGroup.

A.5.6 Med-Fi Covariances: Caveats, with Optical Potentials as an Example

Speaker: Konstantinos Kravvaris (LLNL)

Currently, covariances in ENDF are missing (either completely or partially) for neutron-induced reactions on multiple nuclei. Because the task of providing reliable medium-fidelity covariances will require combining experimental data with improved theoretical modeling, being able to assess the quality of such inputs (and their covariances) is key to achieving robust results. Specifically, in cases of well-measured cross sections with multiple experimental datasets, a single experiment with underrepresented uncertainties can essentially define the evaluation, as well as the corresponding covariance. Thus, while working toward medium-fidelity covariances, researchers need to develop measures that will single out such datasets and alert evaluators for their possible effects. This can be done using standard techniques in statistics, such as bootstrapping and iterative outlier rejection. Consistent use of such techniques is not meant to automatically reject datasets but simply act as a warning that specific experiments may need closer attention during any semi-automated covariance evaluation procedure because they may lead to unrealistically small covariances.

A.5.7 User Perspective on Evaluated Covariances and Experiments

Speaker: Robert Casperson (LLNL)

Some application areas have unique covariance needs that are not well-represented by users of other nuclear data communities; one example of this is Defense Programs, which has an interest in actinide neutron scattering and $(n, 2n)$ cross sections. A major challenge for these two reactions is that they typically have sparse data with limited confirmatory measurements due to the difficulties associated with measuring the outgoing neutrons. For reactions with a large number of experiments, such as neutron-induced fission, it has previously been recognized that experimentalists tend to underreport systematic uncertainties. For reactions with sparse data, such as neutron scattering and $(n, 2n)$, the evaluator loses the ability to estimate these missing uncertainties. A consequence of this was recently seen in candidate ^{239}Pu$(n, 2n)$ evaluations for ENDF/B-VIII.1, where two different evaluations methods arrived at a difference of a factor of two in the cross section uncertainty. It is imperative that the nuclear data community understand when various evaluation methods are applicable, particularly for reactions with limited data.

A.5.8 A Case for Using Robust, Synthetic Data to Improve Nuclear Data Uncertainty Quantification

Speaker: Jacob Forbes (The University of Tennessee, Knoxville)

The nuclear data community requires systematic, quantitative, and reproducible methods for testing evaluated nuclear data uncertainty evaluations. There is a need to develop, test, and demonstrate a systematic approach to validate nuclear data uncertainty evaluations when model assumptions are met. Additionally, it is important to measure the effect of specific assumption violations on the accuracy of these UQs. Understanding the effects of model assumption violations can provide insights into developing methods to augment existing UQ techniques to mitigate these effects. The nuclear data community should support the use of robust synthetic data to develop methods for improving UQ.

A.5.9 Safety-Significant Covariance?

Speaker: William Marshall (ORNL)

Some materials in analysis models are not well-represented in available benchmark experiments used to validate the codes, methods, and ND relied on for the nuclear safety basis. These situations, known as validation gaps, can affect safety margins or require the adoption of compensatory measures to account for the missing data. These measures typically include large reactivity penalties for the potential errors in the data or completely neglecting the presence of significant neutron absorbers in the analysis model. Sensitivity or uncertainty techniques can project the nuclear covariance data to the analysis model and infer the magnitude of the reactivity effect expected from validation errors under the assumption that these errors are well-represented by the covariances. The technical basis for this is robust, and the calculation itself is straightforward, but questions remain regarding the use of the available nuclear covariance data in a safety application in this manner without a complete demonstration of the accuracy of these data. One approach to assessing the data is to apply different covariance libraries to a model of interest and analyzing the resulting differences. In the long run, a more rigorous testing protocol needs to be developed and demonstrated to enable this application of the covariance data.

A.5.10 Integral Experiment Correlations: The Needs and the Challenges

Speaker: Catherine Percher (LLNL)

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook provides many integral benchmarks used extensively for nuclear data validation and adjustment. The fact that many integral experiments are conducted in the same experimental facilities with the same fissile materials and equipment introduces correlations between the experiments. As part of the ICSBEP benchmarking process, evaluators determine the total benchmark uncertainty by rigorously examining all experimental unknowns, but there is no requirement to assess the correlations among the uncertainties of different experiments. Ignoring these correlations when using integral benchmarks to validate nuclear data can result in misinterpretation of validation results. In many cases, a rigorous quantitative evaluation of experimental correlations might not be possible because many of the historical benchmarks are missing major sources of uncertainties. Input from the benchmark user communities is desired to determine whether rigorous quantitative correlations are needed or whether a more qualitative determination would meet the application needs.

A.5.11 Data Adjustments

Speaker: Hany Abdel-Khalik (Purdue University)

This talk covered practical challenges related to the application of Bayesian Inference Methodology for Data Adjustments as applied to nuclear systems models and focused on how implementation for realistic models introduces various issues that are inconsistent with Bayesian theory, thus affecting the quality of the results. Some of these issues include the error compensation phenomenon, in which the adjustments are correcting for unknown sources of errors, or sources that are intentionally excluded from the adjustment procedure. Other issues are due to the presence of modeling errors or non-common sources of errors between the experiments and application conditions, the lack of a reliable approach to measure the similarity between the application and experiments conditions, and the effect of errors or inconsistencies in the prior uncertainties. The talk discusses the need for formal algorithms that can address these practical issues as the role of data adjustments increases to support the fusion of experimental and simulation results to improve predictions.

A.6 FOA-FUNDED PROJECT OVERVIEWS

A.6.1 Fission Product Yield Measurements Using ^{252}Cf Spontaneous Fission and Neutron-Induced Fission on Actinide Targets at CARIBU

Speaker: Guy Savard (Argonne National Laboratory)

The Californium Rare Isotope Breeder Upgrade (CARIBU) facility provides radioactive fission product beams to multiple detectors for the study of fission reactions and decay. In the past, the fission fragment distribution experimental information was mostly obtained on longer-lived isotopes through decay measurements. Yield for shorter-lived isotopes was mostly from modeling to reproduce the measurement on longer-lived isotopes. A new approach has been developed for these measurements that works by detecting isobarically selected ions to directly determine the yield. This technique is essentially independent from the chemical properties of the isotope and can be applied to isotopes with a half-life down to ~25 ms. The multireflection time-of-flight mass separator provides high-resolution mass separation. Analysis for ^{252}Cf is almost complete; there are many data. Although still very preliminary, the new table looks like the old E&R table; however, tables underestimate production of the most neutron-rich isotopes.

Future work is focused on neutron-induced fission at nuCARIBU:

- Cyclotron positioned in CARIBU June 2023
- Mechanical and radio frequency installation November–December 2023
- Transport magnets delivered; chicane assembled offline and ready for installation
- Neutron production target heat exchanger fabricated and undergoing testing

A.6.2 Solving the ^{55}Mn Puzzle

Speaker: Marian Jandel (University of Massachusetts Lowell)

A closer look at the Evaluated Nuclear Structure Data File (ENSDF) evaluation for ^{55}Mn revealed a need for revisiting the data:

- The primary transition to the 212 keV level has practically the same intensity as the only transition depopulating the level
- Other transitions near the ground state seem to have low intensities (statistical de-excitation shows more feeding by a factor of two)
- Data are typically older, obtained with single high-purity Ge (HPGe)–shielded detector
- Pileup/dead time correction and normalization procedures can be complicated
- Gaps and discrepancies found in data
- ENDF to ENSDF correspondence needs improvement

In November 2023-–January 2024, four new HPGe detectors were installed at the University of Massachusetts Lowell reactor, as well as neutron beam monitors and data acquistion electronics. The main developments between June and September were dedicated to new collimation of thermal neutrons. MCNP6 (Konomi) and Geant4 (Jandel) simulations of the full thermal column assembly were designed and guided the setup. The calculations in MCNP6 are underway, including full reactor core and shielding, thermal column, and graphite pile. This work needs to happen in stages, and several calculations are coupled to get the flux at sample position in the center of this setup. Some of the old collimation could be removed; in June 2023, researchers have confirmed the enhancement of neutron intensity by a factor of 11.7 when the collimator is removed: 6×10^6 n/(s cm^2) using BF_3 thermal neutron monitor with University of Massachusetts Lowell's built preamp (R. Krueger capstone project). The design started for new external and indoor collimation; currently, the neutron flux is ~7 $\times 10^6$ n/(s cm^2).

In November 2023-–January 2024, several tune-up experiments were performed for Mn, MnCl, Gd, and Ni. Very preliminary MnCl data were presented. DICEBOX simulations were performed for various-level density models (constant temperature, back-shifted Fermi gas and QRPA/TALYS) and photon strength function models. The effort is ongoing in both simulations and data analysis for rigorous comparison.

Future efforts:

- Plans for new production data measurements in summer 2024
- New detectors will be installed in May and stay near the thermal column for a long time
- Data will be obtained continuously when reactor will be operating
- Dedicated 3–4 weeks or more to Mn data acquisition in May–June
- In July-–August, researchers will collect data on Ni, Cu, Cr

A.6.3 Gamma Rays Induced by Neutrons

Speaker: David Brown (Brookhaven National Laboratory)

Active interrogation with neutrons is a common technique in many applications:

- Inelastic (14 MeV) γ rays are an obvious need
- Less obvious needs:
  - Capture γ rays—neutrons moderate in surrounding material
  - Decay γ rays—these are often background (but could be signal, too)

Unfortunately, the γ-ray data in ENDF is woefully deficient! GRIN is a 3-year NA-22 project with these intended goals:

1. For traditional user—just fix the evaluations!
2. For event-by-event user (correlations!)—need to rethink the API and what data is stored in an evaluation
3. Test the final product

Either way, researchers need to correctly model the reaction, incorporating all experimental knowledge of levels and gamma branching ratios in ENSDF, thermal gammas in ENSDF or EGAF, and thermal capture cross sections in the Atlas of Neutron Resonances.

Many isotopes have been "fixed" from the traditional users' perspective; however, several are in "follow-up" and "remaining to be done" status. To enable event-by-event information (and correlations) in an efficient way, the following is required:

- "Small" files
- Fast sampling
- Correct physics

In general, there are two approaches to incorporate this information: using two emissions in the continuum or all levels and all branching ratios. The best choice is all levels and branching ratios, which will require simulated level scheme, population of all simulated levels, and branching ratios from simulated levels. The implementation will use GIDI (https://github.com/LLNL/gidiplus) as an event generator in GEANT4 using ENDF data in the GNDS format. Significant efforts are being made to stand up a validation framework for outgoing gamma data.

Q&A:

A. Voyles: What level density model are you using? A: It's nucleus dependent.

P. Talou: How will you ensure consistency with ENSDF? A: We use it as source of data.

A.6.4 White Source n-γ Coincidence Measurements of γ-Production Cross Sections at LANSCE: Project Update

Speaker: Keegan Kelly (LANL, presented by Matthew Devlin)

The motivation for this project is active interrogation specifically to identify contents of a container via neutron irradiation. The γ-ray emissions are then used to ID the materials of interest. This requires knowledge of γ-production cross sections, which are effectively equal to $(n, n'\gamma)$ reaction cross sections for many nuclei. It also requires accurate neutron transport for prediction of reactions. The LANSCE facility is well-suited to measure these cross sections—specifically, the CoGNAC array positioned at the Weapons Neutron Research (WNR) facility. The CoGNAC array can measure coincident n-γ reactions using pulse shape discrimination (PSD). Several measurements of γ-only and $(n, n'\gamma)$ reactions were presented for ^{12}C, ^{27}Al, ^{16}O, and ^{28}Si. The data are being communicated to ENDF/B-VIII.0 evaluators and will be included in upcoming evaluations. Follow-on work measuring ^{7}Li$(n, n'\gamma)$ 477 keV γ-production and systematic studies of analysis procedures will be proposed.

Q&A:

J. M. Brown: Why the energy shift between the new data and Boromiza? A: We think Boromiza has CFD issue dependent on the energy of the gamma line.

M. Paris: Why is there a difference in legacy data and resonance in new data at 7.2 MeV? A: We believe that the structure in new data is real.

A.6.5 Fission Product Yield and Gamma-ray Production Evaluation

Speaker: Toshihiko Kawano (LANL)

This work is an energy-dependent fission product yields (FPY) project funded by NA-22. Originally, it was a joint effort of five laboratories (LANL, BNL, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory [PNNL], and Lawrence Livermore National Laboratory [LLNL]). Experimental parts were finished in FY 2021, and LANL, BNL, and LLNL continued in FY 2022 and 2023. With a 3-year extension approved, the LANL/BNL/LLNL project continues until FY 2026. The LANL FPY evaluation includes the following:

- Major actinide data prepared including covariances
- Extending to minor actinides ongoing

- Example of cumulative FPYs for ^{95}Zr for major actinides shows new energy dependencies

Investigation of isomeric ratios (IRs) is underway by LANL, and the calculated IRs are often lower than evaluations or data. However, there are indications that the Madland–England treatment is oversimplified. Differences between theory and data can point to needs for nuclear structure information.

BNL participants made corrections for ^{241}Pu thermal FPY. An issue was logged in 2019 on the National Nuclear Data Center (NNDC) git concerning the FPYs of ^{241}Pu having a hole in the heavy-mass peak. The origin of this issue was investigated, and a correction was made by BNL by rescaling or renormalizing data.

LLNL participants investigated using a particle number projection to build a predictive model for total kinetic energy (TKE) and to improve the prediction of spin distributions in fission fragments. They combine particle number and angular momentum projection (PNP and AMP) to extract spin distribution of fission fragments. The joint AMP + PNP has been implemented and validated, and next, they will fold in probabilities of the population. They also predicted TKE by weighing $\alpha Z_1 Z_2 / D$ with probabilities $p(Z, N)$ in each scission configuration. The proof of concept gives decent agreement in ^{240}Pu, and work will continue with folding in probabilities of the population.

In terms of evaluation of gamma production, this project aims to

- improve both the modeling of nuclear structure and nuclear reactions to produce the first state-of-the-art comprehensive evaluation of gamma-ray production and
- deliver a complete and realistic data library for applications.

LLNL developed a new code to compute excitation strength functions with the finite-amplitude method in a fully microscopic theory. Key points include the following:

- FAM Formalism extended to odd-mass nuclei and finite temperature
- New code can give response to EL and machine learning (ML) operators ($L = 0, 1, 2, 3$) in even-even, odd, or odd-odd nuclei at $T = 0$ or $T > 0$
- Paper in preparation to perform a systematic study of uncertainties
- Dependency of energy functional trend as function of N
- Calculation of the chart of isotopes to follow

Q&A:

D. Neudecker: Have you created covariance data for the FYs? A: We need a new format to properly store covariance info.

A.6.6 Determination of Beta-Energy Spectral Shapes in Fission Products Affecting Reactor Decay Heat and Anti-Neutrino Flux and Addressing Potential Physics Beyond the Standard Model

Speaker: Bertis Rasco (Oak Ridge National Laboratory)

Measuring β-decay is important for several reasons: shape factors can be much larger or smaller than 1, and often, shape factors are not reliably predictable, especially for first-forbidden nonunique β-decays abundantly present in fission products. Extremely productive β spectral measurements were performed from the mid 1950s until the mid 1970s. Research continues to this day with new precision instruments but still with only simple β-decaying isotopes. Why did this productive line of research slow down? What are the

β-energy spectra challenges? Due to unknown nuclear matrix elements, predicting forbidden β decays is challenging; therefore, direct measurements of β energy spectra—and ideally, individual decay branch β energy spectra—are needed.

To address this, the β-Spectrum Module (βSM) – βSM + Modular Total Absorption Spectrometer (MTAS) are being used. This collaboration validated the overall system, which includes tested vacuum, light collection, readouts, linearity, resolution, and calibration performed source measurements with a 2 PMT setup to validate viability of system performed measurements with different geometries (one with a transport tape and one without), and this work extracted consistent results! Currently, the project is validating 2 vs. 7 vs. 12 PMT readouts. Preliminary data have been collected on ^{90}Sr, ^{90}Y, ^{106}Ru, and ^{106}Rh.

Q&A:

R. Venkataraman: Are you interested in ^{99}Tc? A: we are not looking at low-energy data right now but are not limited, so could in the future.

A.6.7 Modern Structure-Based Nuclear Data Evaluations for Basic Science, Nuclear Safety, and Security

Speaker: Mark Paris (LANL)

In the Structure-based Evaluation of Nuclear Data (SBEND) project, the following objectives are identified:

1. Improve effectiveness of US Nuclear Data Program for broad community of ND users
    - Improved analysis and computational techniques
    - Identification of high-priority needs
    - Support for experiment design, analysis, and interpretation
    - Improve availability of data, online and published
    - Dissemination of nuclear reaction and structure data
2. Multiuse or high-impact nuclear data
    - NP basic science users
    - Nuclear energy
    - Nonproliferation
    - Radiation and criticality safety; planetary and space science
3. Support Office of Science/Office of Nuclear Physics–funded research
    - Prioritize ND experiments in 2015 Long Range Plan (LRP) for Nuclear Science
        - Quantum chromodynamics, nuclear astro, fundamental symmetries, and ν (elements of interest)
    - Material categories: structural, controlled, intervening, detector, source

The highest-priority nuclides for this project are H, C, N, and O, with secondary priority given to Li, Be, He, and B. These elements can be found in structural material, controlled substances, shielding materials, detectors, and radioactive sources. At the time of this presentation, ^{7}Li, ^{10}Be, and ^{17}O evaluations have been completed and accepted into ENDF/B-VIII.1 for future release. Work is ongoing for ^{8}Be and ^{15}N. Recent improvements have also been made in physics modeling and theoretical work for predictive models of breakup using existing R-matrix parameters. This can be applied to the $^3He(d, n\gamma)^4He$ and $^3He(t, 2n)^4He$ reactions.

A.6.8 FY24 Project Update for "Designing Nuclear-Data Measurements that Resolve Discrepancies in Existing Data"

Speaker: Denise Neudecker (LANL)

The main question of this project is, "How can we design an experiment such that we credibly reduce unknown systematic uncertainties in a bulk of existing measurements (and thus reduce application uncertainties)?". To demonstrate the methods, this presentation focused on an example of the ^{252}Cf prompt fission neutron spectrum (PFNS). The idea is to create and validate an ML capability to design ^{252}Cf(sf) PFNS experiments, maximally reducing discrepancies in past experiments. To that end, this work used an ML capability to pinpoint measurement features likely related to bias and choose the most significant experiments based on MCNP studies. The importance of ^{252}Cf(sf) PFNS is that it is a Neutron Data Standard and will thus affect many other PFNS, and the team has equipment available at LANL to measure new data and improve evaluations. Bottom line: If you care about the fission source term for your application, you want an accurate evaluated ^{252}Cf PFNS and low uncertainties.

The AIACHNE collaboration is using a sparse Bayesian model to identify potential sources of bias in ^{252}Cf PFNS data. They are extending the Bayesian model with an energy-dependent, multiplicative bias. Sparsity ensures no bias for most energies, but the term is active when the data indicate the need. A sparsity-enducing prior reduces the number of potential biases. The algorithm deals well with a large number of correlated features compared with experimental data. To validate the method and algorithm, tests were performed to correctly identify expected bias due to the ^{6}Li peak. In summary, the AIACHNE ML algorithm allows researchers to explore sources of previously unknown systematic experimental uncertainties.

Q&A:

R. Venkataraman: What is the training data? A: EXFOR data, but need to do a lot of cleaning of the data to be usable.

A.6.9 Two and Three-Body Photodisintegration of the Triton at Energies Below 30 MeV

Speaker: Calvin R. Howell (Duke University and Triangle Universities Nuclear Laboratory (TUNL))

This talk reported on the progress made this year on developing a tritium (^{3}H) gas target and safety system for use in photodisintegration cross section measurements at the High Intensity Gamma-ray Source. This project is carried out by a collaboration of research groups at TUNL and the Laboratory for Laser Energetics at the University of Rochester. Few-nucleon systems provide an environment in which reaction dynamics can be studied using ab initio calculations. This project provides a unique opportunity to measure the **first** kinematically complete cross section data for three-body photo-disintegration of ^{3}H and the **first** angular distribution cross section data for two-body photodisintegraton of this nucleus. These data will enable new studies of how features of the two- and three-nucleon interactions used in state-of-the-art few-nucleon theory influence the calculated observables. The three-body photodisintegration data will enable the concurrent determination of the $^{1}S_0$ neutron-proton (n, p) and neutron-neutron (n, n) scattering lengths for the first time using this reaction. The work is progressing on pace to have the target cell quality-control testing completed and the technical design report ready for safety review around the end of this project year.

Q&A:

M. Paris: What energies will you be measuring the tritium disintegration? A: We chose Al windows to reduce the possibility of neutron background from $(n, 2n)$ reactions at about 20 MeV. We will start at 20 MeV and work our way forward.

A.6.10 Gamma-ray Production Cross Sections for Active Neutron Interrogation with GENESIS

Speaker: Josh Brown (University of California, Berkeley)

The GENESIS mission problem is to provide partial γ-ray cross sections and correlated γ or neutron emission data on high-priority nuclides for active neutron interrogation applications. This project involves taking measurements of neutron-induced γ-ray and neutron emissions, with the University of California, Berkeley, 88 in. cyclotron as the neutron source.

The elements of interest are defined in Table 3. The measurements of C, O, Na, U, Cl, and Fe have already been produced or are under current investigation.

Table 3. Elements of interest for the GENESIS project

Priority	Elements
First	C, N, O, Na Al, Si, Fe, Cu, Pb, W, U, Pu
Follow-up	He, Li, Be, B, Cl, Cr, Mn, Ni, Ge, Br, Cd, I, Cs, La
Remaining	F, Mg, P, S, Ar, K, Ca, Ti, As, Kr, Mo, Sn, Sb, Xe, Gd, Bi, Np, Am, Tm

Accomplishments and future work include the following:

- Publication on array characterization [19]
- Conducted an experiment with a natural carbon target
  - Preliminary γ-ray results
  - Neutron results in progress
- Array expansion—seven new HPGe detectors
- Plan for metallic Na target—calendared for the end of March 2024

Q&A:

P. Brain: What angular granularity do you have with your array? A: Almost too granular, in new set up 5–6 angles with 4–5 detectors at each angle.

A.6.11 Modernization and Optimization of the Evaluated Nuclear Structure Data File & Accelerated Decay Data Evaluation and Development of an Adopted Decay Data Library

Speaker: Elizabeth McCutchan (BNL)

ENSDF is the ONLY comprehensive resource for nuclear structure and decay data. Nuclear structure describes discrete quantized states of excitation energy, half-life, angular momentum, magnetic moment, configuration, and more and emitted radiation including energy, intensity, dipole/quadrupole/..., mixing ratio, and conversion coefficients. Nuclear decay data includes for each decay type: half-life, branching ratio, energy, intensity, coincidences, and more. ENSDF has data for more than 3,300 nuclides, covering more than 100 years of nuclear physics pertaining to nuclear structure, nuclear medicine, nuclear power, astrophysics, stockpile stewardship, and homeland security, to name a few.

Modernization and Optimization of the Evaluated Nuclear Structure Data File

The current ENSDF format has many challenges:

- Nuclear physics does not fit in 80 columns
- Not amenable to ML or AI
- Hard to engage the next generation of nuclear scientists

One major hurdle is that many data are stored in non-standardized comments in the files. This project has migrated from the 80-column ASCII to JSON-based schema, developed a new editor for ENSDF evaluators, and (for the first time!) designed an API for ENSDF.

Accelerated Decay Data Evaluation and Development of an Adopted Decay Data Library

Microcalorimeters are an exciting new development as applied to radiation measurements for nuclear physics and are likely to generate some of the highest-precision decay data to date.

From the 2023 NSAC report on ND, 1 of 14 topics listed as "Challenges and Opportunities" was "Targeted accelerated decay data evaluations." The goals of this project are the following:

- Generate prioritized list of nuclides through consultation with user community (Please send any decay data requests: mccutchan@bnl.gov)
- Develop policies for recommended decay data evaluations
- Train a postdoc to perform decay data evaluations (Postdoc hired and will start April 1, 2024)
- Expand NuDat to visualize and search new evaluations

Timetable of the project:

1. Year 1
    - Identify crosscutting decay data needs and form expert panel to advise
    - Develop evaluation policies and JSON schema
    - Hire and train postdoctoral researcher
2. Year 2
    - Decay data evaluations (metric of 20 ENSDF decay evaluations)
    - Publication of evaluation policies
3. Year 3
    - Decay data evaluations (metric of 20 ENSDF decay evaluations)
    - Extension of NuDat to visualize and query adopted decay data

A.6.12 Benchmarking and Validating Cosmogenic Activation Models

Speaker: Aaron Hellinger (PNNL)

Earth is constantly bombarded by high-energy particles from space. Primary cosmic particles (i.e., protons, alpha radiation) can interact with the N_2 and O_2 in the atmosphere to create secondary cosmogenic particles (e.g., protons, neutrons). These secondary particles are absorbed by materials, creating radioactive isotopes (cosmogenic activation). Understanding production rates is important to evaluate the total surface residency time, transportation options, and storage requirements for low-background detector components. The objectives of this project are the following:

- Develop a software analysis package that estimates cosmogenic activation of materials in Earth's atmosphere (latitude, longitude, altitude)
- Benchmark analysis package, validate flux models, and evaluate cross sections
- Optimize witness samples to accompany detector materials during transport to verify exposure history

This project is currently using NNDC and CMAC functionality to select and evaluate plausibility of specific isotopes acting as witness samples. As of February 2024, LANSCE Nuclear Physics proposals calls have not come out. However, starting in Q2–Q3, this project will

- be purchasing witness materials and storing them at PNNL's Shallow Underground Laboratory,
- fabricate beam targets and holders for irradiations, and
- begin full development of CMAC.

The Witness Sample Selection Process includes the following:

1. A wide range of possible target or product combinations have been gathered from NNDC
    - 5 days $< T_{1/2} <$ 90 days
    - Natural abundances > 20%
    - Reactions evaluated: (n,2n), (n,p), (n,np), (p,n), (p,2p), (p,np)
    - Gamma emitters: intensity > 25%, energy > 500 keV
    - Other reactions are currently being considered
2. CMAC used to gather production rates
    - Richland, Washington, coordinates and elevation (46.2804° N, 119.2752 ° W at 384 ft)
    - Used TENDL-2021 cross sections (0–200 MeV)
    - EXPACS neutron and proton flux
    - Currently investigating JENDL-HE library
    - Currently evaluating results from Los Alamos, New Mexico, coordinates and elevation (35.8800° N, 106.3031° W at 7,320 ft)
    - Materials with largest production rate to cost/kg ratio will be chosen

Current candidates include Rb, Sb, and Co.

A.6.13 Impact of Nuclear Data on Advanced Energy Systems Safety and Operation

Speaker: Germina Ilas (Oak Ridge National Laboratory)

The overarching goal of this project is to **facilitate identifying** nuclear data deficiencies and needs in US Nuclear Data Program databases that have the most effect on advanced nuclear energy systems' safety and operation and to **develop resources** for enabling end user–driven, application-driven improvements in the nuclear data pipeline to address these needs. The significance to stakeholders is going from blueprints to reality: benefiting from DOE support, US private industry is actively engaged in designing next-generation nuclear technologies and developing and deploying advanced nuclear energy systems, which are critical for meeting growing domestic demands for energy security and clean energy as well as ensuring global competitiveness.

Understanding and quantifying the effect of ND and ND uncertainties is essential for the following:

- Ensuring optimal design of advanced reactor concepts and safe operation of deployed advanced reactors
- Designing and safely operating the storage, transportation, and disposal systems for the used fuel that is discharged from these reactors

ND are the bedrock of modeling and simulation from the front end to back end. Because advanced reactor technologies are significantly different than light-water reactors, there are different needs and requirements for applied computational tools and nuclear data. Unfortunately, although a large diversity of resources and knowledge documented over the past 60 years of commercial operational and experimentation is available for light-water reactor assessments, resources to assess ND effects for advanced reactors are very limited. There is a clear need for a benchmark model resource to assess ND effects for advanced reactors beyond integral metrics such as k_{eff} and beyond fresh fuel.

The planned steps toward achieving the overarching goal include the following:

1. Formulate extended advanced reactor benchmark models with irradiated fuel
2. Assess nuclear data effects for advanced reactor key metrics and develop sensitivity coefficients of key nuclides and ND
3. Investigate ND needs for advanced reactors by quantifying uncertainties of key metrics due to ND uncertainties
4. Demonstrate approach to improve critical steps in ND pipeline for rapid testing and evaluation of NNDC ND and associated data processing tools

The impact would be to

- Establish a comprehensive assessment resource that is needed for evaluating and quantifying the effect of ND and ND uncertainties on advanced nuclear energy systems' safety and operation
- Enable identifying ND deficiencies and strengthening the effectiveness of the US Nuclear Data Program databases and ENDF/B's quality assurance system
- Support the ND evaluators in improving the effectiveness and efficiency of the toolsets and resources that are used as a basis for thoroughly testing, evaluating, and validating any ENDF/B release
- Outcomes and benefits of this research will go beyond ND for advanced reactors systems and will facilitate overcoming other existing challenges in applied nuclear science, nuclear energy, isotope production, and national security and nonproliferation

- All created resources will be made publicly available to benefit the ND science and nuclear energy communities, as well as to support academia in fostering learning and further research

Q&A:

Q: What are the computational requirements for the project, and can you record the computational requirements as you go? A: Yes, and we have enough computational resources at ORNL [Oak Ridge National Laboratory], but we also have access to Sawtooth at INL [Idaho National Laboratory] if we need it.

A.6.14 The Berkeley Atlas: A Database of Absolute Cross Sections for Inelastic Gamma-ray Production with 14 MeV Neutrons

Speaker: Patrick Peplowski (Johns Hopkins University)

Applications that rely on neutron inelastic scattering data include explosive detection, buried land mines, planetary science, chemical weapons, unexploded ordinance analysis, drug detection, in vivo body composition, minerals mining and exploration, bulk materials (coal, cement), and more. This typically involves neutron interrogation of an unknown material in which γ-ray energies are isotope-diagnostic. The γ-ray intensities provide material abundances **if** γ-ray branching ratios and γ-ray production cross sections are known. Experimental work has revealed that ND are not sufficient for many elements of interest. Improved ND are required. Prior efforts in this area have identified the following:

- Spurious (not-real) γ-ray peaks
- Unphysical γ-ray emission energy distributions (peak shapes)
- Inaccurate γ-ray production rates

The priorities of the Berkeley Atlas project are the following:

1. Produce an Atlas of cross sections, measured at 14 MeV neutron energy, for use developing improved neutron cross section libraries
2. We have a new technique for making high-precision measurements of γ-ray production cross sections using a DT neutron generator, paired with associated particle imaging (API)
3. Upgrades to existing API system
4. Perform identical measurements on a range of target material of interest for applied nuclear sciences
5. Provide cross section measurements to the NNDC for evaluation and incorporation into future neutron cross section libraries releases

A.6.15 Alpha-Induced Reactions on Light Nuclei—Project Overview

Speaker: Michael Febrarro (Air Force Institute of Technology)

In the Alpha-Induced Reactions on Light Nuclei project, the following objectives have been identified:

1. Experimentally determine α-induced cross sections, secondary γ-ray yields, and neutron spectra
    - $^{7}Li(\alpha,n)$, $^{10}B(\alpha,n)$, $^{11}B(\alpha,n)$, $^{13}C(\alpha,n)$, $^{19}F(\alpha,n)$
2. Perform an R-matrix assessment and dissemination of results

3. Perform calculations to evaluate the effect of these new datasets compared using codes such as SOURCES4C, Geant4, or MCNP

Along with these goals, it is explicitly sought to perform both comprehensive and self consistent measurements. In this context, that means measuring all outgoing channels (neutrons, gammas, charge particles) and using the same experimental setup for all reactions.

There is a dedicated beamline at the University of Notre Dame Nuclear Science Laboratory for the life of the project. There is a full suite of detectors: deuterated scintillator arrays (neutron), GENIE n-type HPGe (γ), and Si detectors (charged particles). There is also dedicated target fabrication and characterization, including an apparatus for enriched ^{12}C foil production; an air-free metallic Li handling area; and isotopically enriched ^{13}C, ^{10}B, ^{11}B, ^{7}Li.

In summary, this 5-year project to measure the (α,n) cross section on light nuclei is well underway! The campaign will provide neutron, gamma-ray, and charged particle data up to 8 MeV for multiple nuclei, and an R-Matrix assessment and impact calculations will be performed to assess the reach of this new nuclear data.

Q&A:

Venkataraman: I noticed you left off ^{16}O, why? A: Rebecca Toomey is already working on this; we also left off Al because of the level of difficulty.

A.6.16 New Measurements of Spontaneous Fission Properties of Pu Isotopes

Speaker: Matthew Devlin (LANL)

The underlying hypothesis for this work is that improved ND can improve non-destructive assay (NDA) for the quantification of Pu content. The typical application is a neutron well counter with a sample inside, measuring the number and time distribution of the neutrons detected. Spontaneous fission neutrons are a relatively clear signal for even-even Pu isotope quantity absent any unlikely actinides (Cf, Cm, and Am isotopes, for example). ND are needed to accurately calculate the expected neutron rate expected from a sample. This includes the following:

- Isotopic sf rates (fission half-lives)
- Neutron number per fission
- Neutron number distribution
- Prompt fission neutron spectra (PFNS)

Measurements will be made at the Chi-Nu array at LANL. Neutron detection is from the EJ309 Liquid Scintillator Array at a 1 m distance from the sample using 54 detectors. Fission detection is from a 12-cell Parallel Plate Avalanche Counter built at LLNL with a total of 18 mg of 99.875% ^{240}Pu.

^{240}Pu

Prior PFNS measurements of ^{240}Pu(sf) are limited—only one modern PFNS measurement with incomplete UQ. Prior data come from past LANL measurements as part of an NCSP-funded effort to measure the PFNS of ^{240}Pu(n,f). Spontaneous fission data were taken between "macropulses" at LANSCE/WNR using a LLNL Parallel Plate Avalanche Counter. Following those measurements, it was found that researchers need more data to properly assess the reaction, specifically with a better fission trigger.

^{242}Pu

The ^{242}Pu data were taken using a legacy foil at LANSCE with the University of Michigan, where a fission chamber was built to house one of these foils (9 mg of ^{242}Pu). The data were taken during the COVID-19 pandemic period over several months when the LANSCE beam was off (there was an extended beam off period). The n-γ correlations from the data were analyzed and published by Marin et al. [20]. These data have now also been shared with the University of New Mexico to extract the prompt fission gamma-ray spectrum. The PFNS from these data will be obtained as part of this project.

There are various high-efficiency neutron counter designs to consider in this project, including the following:

- Plastic bars with interbar thin Gd layers, as in the CEA SCONE array
- Gd-doped liquid scintillator–type detectors, like Carmen

Detailed MCNP-Polimi calculations will be used to develop a suitable high-efficiency, economical detector array design. This detector array will then be used to measure the neutron number distribution for ^{240,242}Pu(sf).

New neutron number distribution measurements could also be made. The Chi-Nu array, or a similar array, could be used to count neutrons as long as the fission tag is adequate. There are examples of a nubar measurement obtained with Chi-Nu in-beam for ^{239}Pu(n,f). However, higher moments of the distribution are difficult to obtain with high precision. So, high–neutron detection efficiency techniques need to be investigated.

In addition to the measurements already described, another goal is to extend all of these measurements to ^{238}Pu. This was not included in the plan yet because of its much higher specific activity. That being said, LANSCE can handle adequate amounts to make sf measurements, and reasonably pure material is available. Researchers would need a very clean fission signal, though, and making a thin ^{238}Pu foil for a fission chamber, for example, will take some effort and may fail. Alternate fission signals can be investigated. Researchers will look into ^{238}Pu measurements during this project and proceed if they look viable.

Q&A:

A. Lovell: Can you also do an n-induced fission measurement? A: Yes, the French may also be interested in this.