WORKSHOP ON NUCLEAR DATA NEEDS FOR NONPROLIFERATION

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ABSTRACT

Recently, the National Nuclear Security Agency, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) hosted the Nuclear Data Roadmapping and Enhancement Workshop (NDREW). This workshop brought together nuclear data experts, data users, and program leads to discuss nuclear data needs for the nonproliferation mission and to recommend a path forward. Results of this workshop will lead to a comprehensive nonproliferation nuclear data strategic document. This paper provides historical context, summarizes workshop discussions, and provides recommendations by the nuclear data community for a comprehensive nuclear data program.

INTRODUCTION

On January 23–25, 2018 in Washington, DC, the National Nuclear Security Administration (NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D, or NA-22) supported the Nuclear Data Roadmapping and Enhancement Workshop (NDREW). Over 110 attendees represented national laboratories, universities, and headquarters, as well as international collaborators and industry representatives. The results of NDREW will be used as input to a nonproliferation nuclear data strategic document to guide DNN R&D funding for the next several years. The strategic document will provide recommendations aligned with mission and technology development priorities. Additional goals of NDREW were:

1. To collect subject matter expert input, including nuclear data prioritization and recommended solutions.
2. To ensure that the resulting nonproliferation strategic document captures the appropriate intersections among ongoing efforts of other programs.
3. To facilitate communication and collaboration among programs and organizations dependent on nuclear data.
4. To increase mutual awareness and understanding of different stakeholder segments of the nuclear data community, including experimentalists, evaluators, end users, and program managers.

The mission of DNN R&D is to fund research that enables those in the field to detect, identify, and characterize (1) foreign nuclear weapons programs, (2) illicit diversion of special nuclear materials, and (3) global nuclear detonations [1]. Nuclear data comprise the fundamental reaction information used as input to neutron and gamma transport calculations and can be the primary source of uncertainty in these calculations. With the increased dependence on transport codes and the desire to be able to model nonproliferation scenarios from first principles, the topic of nuclear data has come to the forefront, with recognition that this information can have a significant, direct impact on users' ability to successfully accomplish their missions. These nuclear data may be cross cutting and can impact several nonproliferation missions, as well as nuclear energy, isotope production, and basic science.

Since 2007, DNN R&D has invested in nuclear data improvements. Examples include radiochemistry for americium cross section measurements, development of CGMF [2] and Fission Reaction Event Yield Algorithm (FREYA) [3], computational tools integrated into MCNP [4] transport code for processing correlated neutron and gamma emission from fission, actinide cross section measurements using surrogate methods, and $^{19}F(\alpha,n)$ cross section measurements.

BACKGROUND

NDREW is the result of several meetings and discussions over the past several years. After a 2014 US Nuclear Data Program (USNDP) review by the US Department of Energy, Office of Science (SC) Office of Nuclear Physics (DOE NP), it was determined that the USNDP should obtain feedback from stakeholders on nuclear data needs and priorities and then pursue experimental studies to address nuclear data gaps. To address these recommendations, DOE NP and DNN R&D hosted the Nuclear Data Needs and Capabilities for Applications (NDNCA) workshop on May 27–19, 2015 [5]. The workshop collected nuclear data needs from all applications and compiled a comprehensive list of deficiencies to address. The result was the realization that many nuclear data needs are cross cutting, impacting multiple programs. Therefore, it was determined that collaborative efforts would be useful.

Shortly after NDNCA, the Nuclear Data Working Group (NDWG) was formed to facilitate cross program communication [6]. The working group was made up of representatives designated by program offices with an interest in nuclear data collaboration. The NDWG identified and prioritized several of the most important cross cutting nuclear data needs and formed a proposed solution and several general recommendations for funding nuclear data efforts. This was presented to 25 federal program representatives at the Nuclear Data Exchange Meeting (NDEM) on April 15, 2016 in Washington, DC. NDEM provided an opportunity for critical conversations between the nuclear data community and program managers, focusing on a collaborative path forward to solving nuclear data needs.

After the NDEM, program managers of several offices created a Nuclear Data Interagency Working Group (NDIAWG) chaired by DOE NP to coordinate nuclear data funding between participating program offices, including DNN R&D. The result was the NDIAWG Funding Opportunity Announcement (FOA) released in 2017 and managed by DOE NP [7]. Participants in the FOA included DOE NP, the Office of Nuclear Energy (NE), and the Isotope Program (IP) of the Office of Science (SC), DNN R&D, and the Domestic Nuclear Detection Office (DNDO)

of the Department of Homeland Security (DHS). The 2017 FOA resulted in funding for three projects:

1. Improving the Nuclear Data on Fission Product Decays at CARIBU
   PI: Savard, Guy (ANL)
2. Novel Approach for Improving Antineutrino Spectral Predictions for Nonproliferation Applications
   PI: Kondev, Filip (ANL)
3. ^{238}U(p,xn) and ^{235}U(d,xn) $^{235–237}$Np Nuclear Reaction Cross Sections Relevant to the Production of ^{236g}Np
   PI: Fassbender, Michael (LANL)

The 2018 NDIAWG FOA was released March 26, 2018 [8]. Participants include DOE NP, the Advanced Scientific Computing Research (ASCR) program within SC, NE, DNN R&D, and Experimental Science (NA-113) of NNSA. The focus of this FOA is based in part on the input from NDREW participants and includes improvements to the nuclear data pipeline to enable incorporation of nuclear data into the databases more readily, application of advanced computing techniques to nuclear data, nuclear data measurements for advanced reactors, and new fission yield evaluations.

It is anticipated that the NDIAWG FOA will be an annual call and that subsequent workshops will be held to continue communication between program offices, nuclear data producers, and nuclear data users from all applications.

HIGH LEVEL PRIORITY NEEDS

As a result of the participant input from NDREW and the previous workshops and meetings discussed above, several high-level cross-cutting needs came to the forefront. The needs listed below look towards the ultimate goal to provide improved nuclear data to the user with quantified uncertainties that have mission impact.

- Evaluate cumulative and independent fission yields of ^{235}U, ^{238}U, ^{239}Pu, as well as many of the minor actinides
- Conduct inelastic scattering measurements on ^{235}U, ^{238}U, and ^{239}Pu in the energy range of 1 keV–3 MeV
- Solve the production and destruction of actinides within the actinide network
- Improve passive neutron source terms to include:
  - measurements of the neutron multiplicity and energy spectrum from spontaneous fission
  - (α,n) cross section measurements and/or evaluations, measurements of neutron emission spectrum from (α,n) reactions, and studies of stopping powers
- Conduct application-specific benchmark experiments to test differential data, and apply uncertainty/sensitivity methods to systematically determine nuclear data deficiencies
- Update the database infrastructure and modernize the methods used to produce evaluated data to make data more readily available to the user
- Improve the ability of transport codes to model observables from nondestructive (NDA) measurements, including discrete gamma energies from neutron capture and inelastic scattering and correlated fission emissions.

- Ensure that each new set of data includes covariance data and that the data can be processed for use in the codes

NONPROLIFERATION PROGRAM NEEDS

As part of NDREW, program managers from various nonproliferation offices discussed mission-driven nuclear data needs and current funded projects. Nuclear data users provided information on their nuclear data needs based on inconsistencies between calculated and measured data. Those needs are listed below.

- Fission cross sections and fission yields of actinides induced by neutrons from thermal to fast energies
- Fission products existing < 1 second
- The time-dependent neutron/gamma intensities resulting from short-lived fission fragments produced by fast neutron fission
- Cross sections for actinides other than ^{235}U or ^{239}Pu
- Production and decay data for ^{153}Sm, ^{115m}Cd and Xe isotopes
- Fission cross sections and correlated neutron and gamma emission data for 6–9 MeV incident gammas
- The ability to model systems from first principles, where reality is not known
- Simulation tools that adequately model correlated neutron and gamma decay from neutron- and gamma-induced fission and from inelastic scattering
- Capability to propagate nuclear data uncertainties through a simulation

NDREW SESSION SUMMARIES

NDREW included several half-day discussion sessions to solicit input from all participants and to facilitate discussions on proposed solutions. Session participants were asked to focus their conversation on nuclear data that will impact nonproliferation missions. They were also asked to address improvements needed to the entire nuclear data pipeline to ensure the data is accessible to the user. The following is a summary of the input from the NDREW session participants and does not necessarily reflect the priorities of the funding agencies or the contents of the resulting DNN R&D nuclear data strategic document.

Fission I: Independent & Cumulative Yields
Session Leader: Patrick Talou, Los Alamos National Laboratory

This session focused on the required effort to reevaluate fission yields, including measurements and theory development. The primary topics discussed were:

- Creation of an open source code for fission yield evaluation
- Measurements of independent yields as a function of incident neutron energy
- Measurements of cumulative yields as a function of incident neutron energy
- Top priority isotopes: ^{235}U, ^{238}U, and ^{239}Pu
- Secondary isotopes: those of Cm, Am, Np, Th
- Participation in the International Atomic Energy Agency's (IAEA's) upcoming coordinated research project (CRP) on fission yield evaluations
- Develop capability within ENDF [9] format to handle covariance data of fission yields

Fission II: Prompt Neutron and Gamma Ray Emissions
Session Leader: Sara Pozzi, University of Michigan

This session examined the state of nuclear data for prompt neutrons and gamma rays from fission. The primary topics discussed were:

- Reexamination of ^{252}Cf spontaneous fission neutron and gamma emission measurement as a standard before anything else
- Measurement of prompt signatures such as neutron angular distributions and multiplicities at a short time scale (sub-ns)
- Induced fission emission data of ^{235}U and ^{239}Pu
- Spontaneous and/or induced fission emission data for: ^{233}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{244}Cm, and ^{250}Cf
- Signatures of interest:
    - Energy spectra for prompt neutrons and gamma rays, multiplicities
    - Correlations between the number of neutrons and the energy distribution of the neutrons
    - Angular correlations of the neutrons
    - Correlations between neutron and gamma ray emissions
- Development of transport codes such as CGMF, FREYA, MCNPX-PoliMi to model the prompt and delayed neutrons and gamma rays
- The need for code development efforts to validate experimental data

Fission III: Decay Data
Session Leader: Elizabeth McCutchan, Brookhaven National Laboratory

This session examined the status of decay data to support the evaluation of fission yields and beta-spectra data related to reactor antineutrino studies. The primary topics discussed were:

- Priority fission products: ^{147}Nd, ^{131m,133,133m,135}Xe, ^{133}Cs, ^{153}Eu, ^{141}Ce, and ^{104}Ru
- Branching, half-lives, gamma ray energies, decay heat energies, and the shape of the beta decay spectrum for isotopes of interest
- Uncertainty/sensitivity studies to determine the key pieces of nuclear data that impact a fission product of interest
- A new application programming interface (API) for evaluated nuclear structure and decay data files (ENSDF)

It was also requested that users communicate decay data priorities for evaluation to the National Nuclear Data Center (NNDC).

Actinide Cross Sections
Session Leader: Susan Hogle, Oak Ridge National Laboratory

This session addressed experimental measurement and theory for actinide neutron absorption cross sections and decay as part of a web of actinides created and depleted in high flux environments. A key challenge is that many actinides are short lived and/or difficult to isolate, but knowledge of their cross sections is required. Primary topics discussed were:

- Isotopes of interest are:
  - ^{235}U, ^{237}U, ^{237}Np, ^{238}Np, ^{238}Pu, ^{236}Pu and ^{239}Pu
  - ^{241,243}Am and Cm isotopes, which are the gateway for the production of heavier actinides
- (n, γ), (n,f) and (n,2n) are priority cross section measurements and evaluations are required
- Decay properties require improvement, specifically for the short-lived actinides
- Surrogate measurements of short lived actinides would benefit from integral validation measurements
- Improved capabilities in structure-informed reaction modeling, particularly for (n, γ) and (n,2n) reactions
- Theoretical models will be required to evaluate data and fill in gaps
- Evaluation and validation of new and existing data are needed

Gamma-Induced Reactions
Session Leader: Brian Quiter, Lawrence Berkeley National Laboratory

This session examined the nuclear data gaps in photonuclear reactions, such as photofission (γ, f), photonuclear neutron release (γ, n), and the observables from those reactions. Priority topics discussed were:

- Photonuclear cross sections of ^{235}U, ^{238}U, and ^{239}Pu
- Incident neutron energies between 6 and 20 MeV, with emphasis on 6 and 9 MeV for active interrogation
- Prompt neutron multiplicity and angular distribution
- Delayed neutron and gamma data
- Fission product yields from photofission
- A better understanding of the gamma induced neutron background may be helpful
- Further investigation of nuclear resonance fluorescence (NRF)

Neutron Capture and Associated Spectra and Inelastic Scattering and Associated Spectra
Session Leader: Lee Bernstein, Lawrence Berkeley National Laboratory / University of California, Berkeley

These sessions focused on capture gamma and associated spectra, as well as inelastic scatter and associated spectra. The priority was to address the observable gamma-ray spectra following (n,γ) and (n,n'γ).

- Inelastic scatter cross sections on ^{238}U, ^{235}U and ^{239}Pu from 1 keV to 3 MeV are a priority need
- Discrete gamma energies are needed for MCNP models of active neutron interrogation
- Isotopes or materials of interest include structural materials, those used in nuclear materials processing and light nuclei
- At higher energies, (n,n' γ) becomes increasingly important relative to (n γ), and the quality and quantity of the data decrease significantly

(alpha,n) Reactions
Session Leader: Matt Devlin, Brookhaven National Laboratory

This session focused on (α,n) reactions and their neutron emissions. This is important data for nondestructive analysis (NDA) techniques to understand the passive neutron source term. Priority topics discussed were:

- Priority isotopes: ^{19}F, ^{17}O, and ^{18}O, Li, C, and Cl
- Data required for incident alpha energies ranging from under 1–9 MeV
- Outgoing neutron energy spectra requires new measurements
- Benchmark studies and collection of thick-target data for the high-priority isotopes
- Evaluations of recently obtained data
- Update of SOURCES4C code to provide improved passive neutron information from (α,n) reactions and spontaneous fission

Development of Benchmark Exercises
Session Leaders: Rian Bahran, Los Alamos National Laboratory, and Sean Stave, NNSA, Safeguards Technology

This session began a conversation on the development of benchmarks for nonproliferation missions that can be used to identify nuclear data deficiencies and validate existing and new differential data. The main takeaways from this session were:

- Uncertainty/sensitivity tools are needed to analyze the benchmark data
- Criticality benchmarks are not always appropriate for subcritical applications
- Existing experiments may be benchmark quality and can be used for validation
- Further discussion is required to determine the requirements

Uncertainty, Sensitivity, & Covariance
Session Leader: Brad Rearden, Oak Ridge National Laboratory

This session examined the current uncertainty, sensitivity, and covariance analysis capabilities required to determine nuclear data deficiencies and understand the impact of nuclear data uncertainties on individual missions. Priority topics discussed were:

- Uncertainty/sensitivity tools require new capabilities for nonproliferation applications
- Sensitivity and uncertainty quantification analysis tools are needed for fixed source problems relevant to passive and active interrogation
- Uncertainties in inverse calculations based on NDA are important
- Tools should be broad in scope, automated, and plug-and-play
- Sensitivity and uncertainty studies are needed for:
    - Correlated treatment of gammas and neutrons emitted from fission
    - Reactor depletion
    - Actinide cross sections
    - Decay chains

Data Processing & Transport Code Needs
Session Leaders: Brad Rearden, Oak Ridge National Laboratory and Teresa Bailey, Lawrence Livermore National Laboratory

This session focused on data processing and transport code needs for the proper use of existing and new types of nuclear data. Nuclear data transport codes are required to process nuclear data for use in transport models and are required to provide the user with robust nuclear data. Priority topics of discussion were:

- Treatment of particles emitted from fission including prompt neutron-neutron and neutron-gamma correlations, timing of prompt emissions, and delayed emissions from decay of fission fragments
- Temperature resolution for neutron thermal scattering law data
- Complete photofission libraries and delayed emission treatments for active gamma interrogation
- Capture gamma emission
- Increased validation, verification, and benchmarking capabilities for nuclear data across several nonproliferation application spaces
- More complete ENDF libraries
- Improved linkage of ENDF to ENSDF

Targets, Facilities and Detector System
Session Leaders: Jason Burke, Lawrence Livermore National Laboratory and Todd Bredeweg, Los Alamos National Laboratory

This session examined the current capabilities in nuclear data measurement target production, as well as facilities and detector systems used for nuclear data experiments. Priority topics discussed include:

- Meeting all the nuclear data requirements is more than a single organization can accomplish, and multiple office resources should be leveraged
- The cost of isotope targets can be prohibitively expensive
- The time required to produce targets can be too long
- Thin target production capabilities for actinides is limited except for electrodeposition or evaporation which is not optimal for many experimental needs
- There is a shortage of enriched actinides to enable low uncertainty nuclear data experiments
- Top facility needs:
    - A setup specifically dedicated to neutron scattering measurements
    - A setup for transmission experiments
    - A rabbit sample transfer system for the Device Assembly Facility (DAF) at the Nevada National Security Site
- Detector needs:
    - Systems compatible with neutron scattering experiments
    - Detection systems for gamma-induced fission measurements

DISCUSSION AND CONCLUSIONS

Communication between the nuclear data community and program managers has shown great benefit in the past two years, providing valuable input to funding agencies on critical needs and best practices for nuclear data funding. Of these best practices, the incorporation of a USNDP point of contact at the initiation of a measurement is vital to the subsequent evaluation; this requirement was included in the NDIAWG FY18 FOA. In addition, the importance of the nuclear data pipeline, including evaluating, processing, and testing of data to ensure that the data are provided to the users was emphasized. Additionally, the opportunity for program managers to share nuclear data priorities and ongoing projects with the nuclear data community helps them plan and propose nuclear data efforts that have mission impact. This is particularly important to universities who are not integrated as well into mission needs, but who are an important part of the US nuclear data infrastructure.

Some of the programmatic takeaways from NDREW include:

1. Representation at Nuclear Data Week, the annual meeting of the USNDP and the Cross Section Evaluation Working Group (CSEWG), will be critical for ensuring that each programs' needs are considered and addressed as new ENDF files are developed.
2. Workforce development and facility maintenance are important for ensuring long-term improvements in nuclear data. Ongoing efforts will require collaboration among multiple laboratories and universities, maximizing the strengths of each.
3. New measurement and evaluation efforts must be well integrated into the USNDP.
4. All nuclear data efforts' end goal should be the incorporation of that data into the databases with the goal of reaching the end users.
5. Continued communication, collaboration and cooperation between mission programs with input from the nuclear data community will be key to ensuring that nuclear data funding provides the highest level of mission impact while improving efficiency. The NDIAWG FOA has demonstrated its utility for this purpose.
6. Continued communication between nuclear data users and producers is important to determine nuclear data priorities and to keep the nuclear data producers focused on mission needs. There is consensus from NDREW participants that this communication is useful.
7. New nuclear data projects should address the modeling and data processing required to use the new data. As nuclear data and covariances become more complex, the processing codes will require enhanced capabilities to handle the large files.
8. NDREW participants concurred that they found the workshop valuable since it initiated conversation and presented new opportunities for collaboration among data users, nuclear data experimentalists, and evaluators.

Results from NDREW, combined with the input from previous meetings and DNN R&D mission priorities, will be used to develop a strategic document prioritizing nuclear data activities for DNN R&D to inform decision-making for the office in subsequent years.

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