Second Report of the Nuclear Data Charge Subcommittee of the Nuclear Science Advisory Committee

March 19, 2023

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1 Executive Summary

In September 2022, the Department of Energy (DOE) and National Science Foundation (NSF) Nuclear Science Advisory Committee's subcommittee on Nuclear Data (NSAC-ND) released a report highlighting the critical importance of the nuclear data curated by the US Nuclear Data Program (USNDP) for clean energy generation; national security; nonproliferation; medical applications, and space exploration, as well as basic science. This second document from the NSAC-ND uses input from that report to lay out a strategic plan comprised of fourteen (14) prioritized recommendations that would enhance and advance DOE-Nuclear Physics' stewardship of nuclear data. The first three recommendations focus on the existing core USNDP capabilities:

- Supporting the nuclear structure evaluation workforce to improve the currency, consistency, and accessibility of the Evaluated Nuclear Structure Data File (ENSDF) (section 2.1);
- Enhancing nuclear reaction evaluation within the USNDP in support of the Evaluated Nuclear Data File (ENDF) through expansion of the workforce and integration of high-performance computing, automation, and machine learning (section 2.2), and
- Establishing recommended values for fundamental nuclear properties, such as the atomic mass evaluations complied in the AME, NUBASE and similar databases (section 2.3).

These are followed by eight (8) recommendations for new cross-cutting initiatives involving measurement, theory, and evaluation to address outstanding nuclear data needs that are not directly addressed by the above efforts. These new initiatives require a highly trained, diverse workforce that includes personnel with expertise from both inside and outside the nuclear science community. As such, many of these initiatives would be best accomplished via a Topical Nuclear Data Collaboration (TNDC) made up of members of the USNDP together with domestic and international stakeholders with subject matter expertise. A TNDC would embed members of the USNDP in each nuclear data endeavor in order to ensure their understanding of the underlying experimental and theoretical data sources, and to maintain an up-to-date understanding of the needs of the relevant application areas. These include new cross-cutting nuclear data initiatives in the following areas:

- Astrophysics: Establishing a coordinated effort to improve evaluation and modeling in nuclear astrophysics for stellar dynamics, multi-messenger astronomy and nucleosynthesis (section 2.4);
- Statistical nuclear structure: Developing and maintaining nuclear structure evaluation beyond discrete states, including nuclear level densities, photon strength functions, optical model parameters and photonuclear data for improved reaction modeling, and exploring nuclear structure at finite temperature (section 2.5);
- Fission: Establishing methods for correlated fission data evaluations, including cross sections, fragment yields, $\nu(A)$ and $\nu(E_n)$ for nuclear energy, national security, nonproliferation and basic science (section 2.6);

- Radioactive Decay: Strengthening and accelerating measurement, evaluation and dissemination of decay data for targeted nuclides of high-value for national security, nonproliferation and medical applications (section 2.7);
- Neutron-induced data reactions and structure: Providing comprehensive, consistent neutron-induced structure and reaction data (section 2.8) for nuclear energy, national security, nonproliferation and planetary nuclear spectroscopy;
- Charged-particle stopping powers: Determining charged-particle stopping powers for detector design, space effects and ion beam therapy (section 2.9);
- Expanded reaction modeling: Enhancing nuclear reaction modeling capabilities to include compilation and evaluation of high-energy and charged particle induced data for space exploration, radionuclide production and ion beam therapy (section 2.10); and
- Fusion power: Developing nuclear data for fusion energy systems including tritium production and materials damage cross sections (section 2.11).

In addition to these eight new cross-cutting initiatives, three (3) recommendations are presented to modernize and increase the efficiency of the nuclear data infrastructure, involving:

- Modern Data Formats: Expanding the development of new nuclear data formats to accommodate existing and new nuclear data types and improve access by modern software systems (section 2.12);
- Artificial Intelligence and Machine Learning (AI/ML) tools: Developing, designing, and incorporating modern methods using AI/ML tools to improve the nuclear data evaluation process (section 2.13), and
- Data Preservation: Creating an infrastructure for open data and data preservation for use by the entire nuclear science community (section 2.14).

These fourteen recommended initiatives to enhance nuclear data capabilities will require approximately a $6.5M annual increase in ongoing NP support of the USNDP in fiscal year 2023 dollars. These initiatives will likely require more than 5 years to completely implement due to the length of time needed to recruit and train new nuclear data researchers. This relatively modest proposed investment will help ensure that the fruits of the investment in nuclear data research carried out by DOE-NP and its collaborators are brought to bear to address some of the most important needs of our nation and the world.

To ensure effective execution of this proposed plan, section 3 of this report presents an overview of recruitment, training, and retention goals for the USNDP including a mutually agreed upon code of conduct to enhance collaboration, communication, and inclusion.

Finally, section 4 identifies key facilities and instrumentation required to address these nuclear data needs. This includes a short review of target fabrication capabilities (section 4.1), reactors (section 4.2), neutron beam (section 4.3), gamma-ray (section 4.4), light- and heavy- stable ion (section 4.5), high-energy (section 4.6) and radioactive ion beam (section 4.7) facilities. The report also includes a more complete appendix of experimental facilities than previously compiled and includes new input provided for eight (8) facilities.

2 Challenges and Opportunities for Nuclear Data

For many decades virtually all of the USNDP efforts involved the maintenance of the flagship nuclear structure and reaction databases, the Evaluated Nuclear Structure Data File (ENSDF) and the Evaluated Nuclear Data File (ENDF), respectively. In 2017, these two activities accounted for more than 90% of the USNDP funding, with structure data compilation and evaluation alone accounting for more than 70% of DOE-NP base support. The result was a USNDP that plays a crucial role supporting nuclear structure research through the maintenance of ENSDF and the publication of nuclear mass number or *A*-chains in Nuclear Data Sheets (NDS). The USNDP also plays a central role in coordinating the Cross Section Evaluation Working Group (CSEWG), charged with maintaining ENDF and contributing to an annual edition of NDS that includes a broader range of reaction-related work.

This picture started to change following the 2015 Nuclear Data Needs and Capabilities for Applications (NDNCA) workshop [Ber15], which led to a growing awareness of the importance of nuclear data to a wider range of applications with societal benefit whose data needs are often outside those of low-energy nuclear structure. The NDNCA meeting led to the founding of the Nuclear Data Working Group (NDWG), comprised of application subject matter experts nominated by program managers in the Nuclear Data Interagency Working Group (NDIAWG), both of which are described in section 2.2.1 in the first NSAC-ND report. The NDIAWG supports a series of nuclear data activities relevant to nonproliferation, national security, nuclear energy and isotope production that led to a doubling of support for the USNDP from 2017 to 2022, with the vast majority of funding coming from non-NP programs. Most recently, the NDWG and NDIAWG have been seeking to expand this effort to include nuclear data activities relevant to space exploration and fusion energy.

The new NDIAWG-sponsored activities greatly enhance nuclear data for basic and applied science, but they also present a challenge to the USNDP since much of the new data generated requires experimental work and evaluation expertise and capabilities beyond those being used to maintain ENSDF and ENDF. These new nuclear data efforts also require significant changes in the way that the USNDP interacts with the basic and applied science and engineering communities it serves. One way to address these challenges would involve carrying out an engineering study to determine how best to streamline the flow of data to application areas and to convey the needs of the applications to the USNDP. A proper engineering study could facilitate revisions of the existing nuclear data pipeline [Ber19a, Ber19b] to be more of a closed loop where evolving application needs can help shape the focus of the USNDP and aid in workforce development.

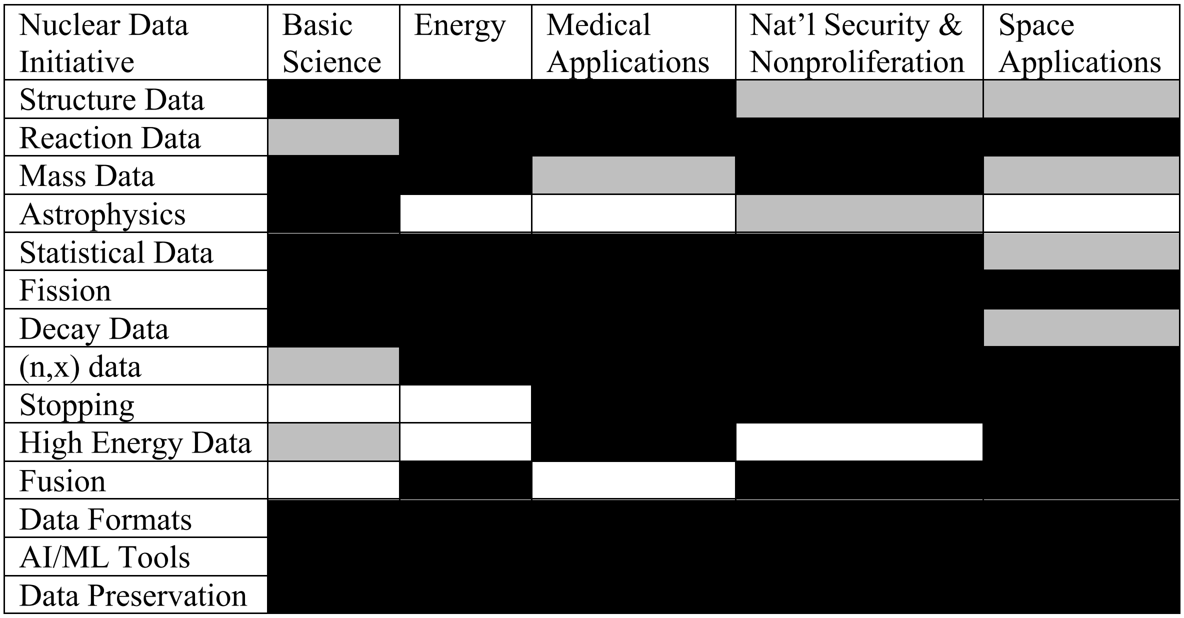
The application areas mentioned above are discussed in Section 4 of the first NSAC-ND report. These applications may have different goals, but many of them share common nuclear data needs. Some of these are readily identified. For example, nuclear energy, national security, nonproliferation and portions of space applications and isotope production rely on well-quantified nominal values and associated uncertainties for fission and (n,x) data. However, accurate nuclear reaction evaluation introduces additional, “hidden,” nuclear data dependencies. These include resolved and unresolved level energies, photon data, and decay branching ratios. The result is a lengthy list of needs which would greatly exceed the capacity of the USNDP staff to address entirely on its own.

Fortunately, the USNDP serves as an organizational hub for national nuclear data activities. This is exemplified by its leadership of the annual Workshop for Applied Nuclear Data Activities (WANDA) organized by the NDWG, that helps identify and develop plans to address nuclear data needs and the Cross Section Evaluation Working Group (CSEWG) that works to maintain and improve the Evaluated Nuclear Data File (ENDF) reaction library. These efforts are inherently *cooperative and collaborative*, with numerous programs contributing to the common goals of improving nuclear data and providing a roadmap to address the growing list of identified nuclear data needs.

In this report we identify three (3) core capabilities of the USNDP and eleven (11) cross-cutting nuclear data initiatives that offer an opportunity to enhance and advance DOE-NP's stewardship of nuclear data. Each initiative includes four parts:

1. Issue: Identification of a crosscutting nuclear data need;
2. Background: A discussion of how the initiative is related to the need;
3. Recommendation: A recommendation of how to carry out the initiative, including an estimate of the additional workforce needs and a recruitment/training timeline;
4. Impact: The benefit that would result from carrying it out.

Figure 1.1 below shows the relationship between the nuclear data initiatives and the application areas presented in the first NSAC-ND report (e.g., Basic Science, Nuclear Energy, Medical Applications, National Security, Nonproliferation and Space Applications). This is effectively a two-dimensional projection of Figure 1.1. from the first report.



Nuclear Data Initiative	Basic Science	Energy	Medical Applications	Nat'l Security & Nonproliferation	Space Applications
Structure Data	■	■	■	▨	▨
Reaction Data	▨	■	■	■	■
Mass Data	■	■	▨	■	▨
Astrophysics	■			▨	
Statistical Data	■	■	■	■	▨
Fission	■	■	■	■	■
Decay Data	■	■	■	■	▨
(n,x) data	▨	■	■	■	■
Stopping			■	■	■
High Energy Data	▨		■		■
Fusion		■		■	■
Data Formats	■	■	■	■	■
AI/ML Tools	■	■	■	■	■
Data Preservation	■	■	■	■	■

Figure 1.1: Interrelationships between the nuclear data initiatives presented in this report and the nuclear data needs sections in Section 4 of the first NSAC-ND report. Black and grey cells show direct and indirect applicability of the nuclear data topic to the application respectively.

In many of these cases, the recommendation involves the formation of a *topical nuclear data collaboration* (TNDC) centered on members of the USNDP and involving other Federal or non-Federal partners. A TNDC would potentially span multiple laboratories, federally-funded research and development centers, and universities that would help provide the resources, experimental, theoretical and evaluation capabilities necessary to address a nuclear data need. Furthermore, each TNDC would include a plan to recruit, train and retain a diverse, equitable and inclusive workforce needed to address its goals. A schematic of one potential TNDC is shown in Figure 1.2.

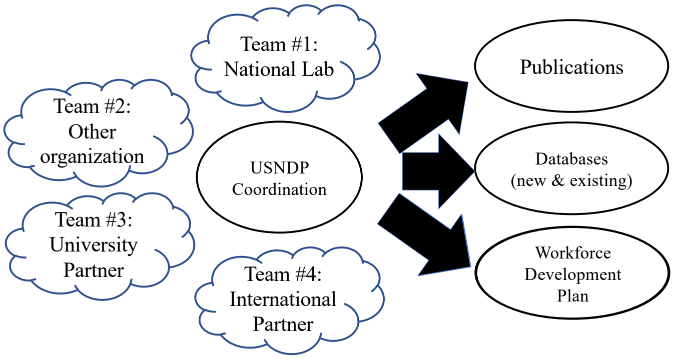


Figure 1.2: Notional schematic of a potential Topical Nuclear Data Collaboration. Partners will vary depending on the topic, but a USNDP member should also be included.

USNDP researchers would be equal partners in the TNDC. They would be expected to publish in the main peer-reviewed journals used by researchers in these application areas (e.g., Physical Review, Astrophysical Journal, Nuclear Science and Engineering, Radiochemica Acta, etc.) as well as contributing to existing and new databases and journals maintained by the USNDP. This expansion of the workforce would draw on the distributed nature of the USNDP across 9 national laboratories and universities to ensure that the right subject matter and nuclear data expertise is present in the TNDC. The expansion of the USNDP workforce would also help ensure that all of the centers maintain a "critical mass" of intellectual capability. The expanded USNDP would require a new set of more broadly-based metrics to ensure that it accurately represents the wider body of work carried out by the new members of the workforce.

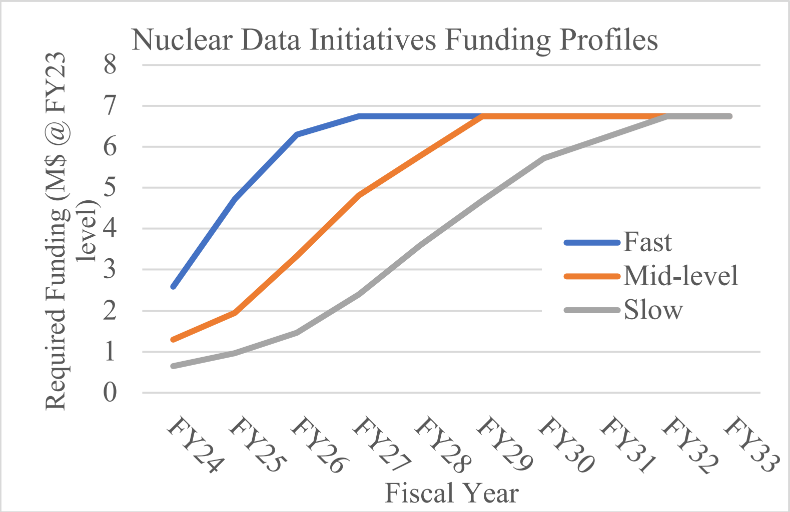


Figure 1.3: Three potential funding profiles for the nuclear data initiatives described in Section 2 of this report.

The expansion of the USNDP required for all of these initiatives would require roughly a 65% increase in the USNDP budget and would take 3-4 years minimum to initiate due to the extensive training required to produce a productive nuclear data researcher. Several potential expansion/funding profiles are shown in Figure 1.3.

The eleven new crosscutting nuclear data initiatives described in this report complement the important nature of the structure, reaction and mass evaluation activities being carried out by the 16 current members of the USNDP. The first three subsections presented below use the same 4-part format described above to highlight the need to maintain robust evaluation capabilities in nuclear structure (ENSDF), reactions (ENDF) and mass evaluations.

2.1 Supporting Structure Evaluation Capabilities

Issue: There is an average of 10 years between updates of any mass chain. The gap in time between publication of a measurement and incorporation into the ENSDF library is too large, impacting downstream nuclear applications.

Background: Evaluation of measured decay and structure properties of known levels in all nuclides for the Evaluated Nuclear Structure Data File (ENSDF) accounts for the majority of the effort carried out by the USNDP. These very detailed evaluations are primarily performed by the 13 nuclear structure evaluators in the US who critically review all published experimental nuclear structure measurements. The USNDP is the only body charged with the continuation and improvement of ENSDF.

ENSDF, the international standard for nuclear structure information, must be kept current to ensure the basic and applied nuclear science communities have the most up-to-date and reliable data regarding discrete levels. It also must be internally consistent and consistent with other databases, including, most notably, the Evaluated Nuclear Data File (ENDF). The data also need to be made available in formats useful to the community and with modern data management and dissemination approaches.

For ENSDF to remain an invaluable resource for basic and applied science, the database must be kept as current as possible. There is an average of 10 years since the last update of any nuclide. For researchers to get the most current values of the properties of a given nuclide, they must (a) find the relevant properties in ENSDF, (b) find any new measurements of those properties as compiled in the Experimental Unevaluated Nuclear Data List (XUNDL) database, (c) search the literature for any relevant updates that have not yet been compiled in XUNDL, and (d) combine all the above information into a best, new value. In other words, the researcher must do the work of a nuclear structure evaluator. For nuclides not updated in 10 years or more, this could place a substantial burden on researchers in basic science, who will likely just use the ENSDF values which could be up to a decade out of date. Applied researchers are even more likely to simply rely on the outdated ENSDF values.

The ENSDF database is often used as a source of nuclear decay data for ENDF, the world-standard reaction database that is critical for nuclear energy, nuclear security, and many other important applications. Up-to-date structure and decay data are critical components of the vast panoply of applications that rely on ENDF. Outdated ENSDF data also impact the medical isotope community because the Medical Internal Radiation Dose (MIRD) database is largely derived from ENSDF. Outdated decay properties can reduce the cost-effectiveness of isotope production, which relies on nuclear data to determine exposure times in reactors and bombardment times in accelerators. Even more critically, outdated decay data can impact dosing decisions made by doctors that pose a safety risk for patients. Many other examples can be given for the need for reliable and accurate nuclear structure data, further supporting the need to incorporate the evaluated structure and decay data into the ENSDF database in a timely manner and keep ENSDF as current as possible.

In a typical year, investments by funding agencies in measurements are nearly 50 times higher than the funding for evaluations needed to incorporate those measurements into the databases required for applications. The result is a poor scientific return on investment.

The nuclear data community widely agrees that a 10-year average frequency in ENSDF mass chain evaluation is too long and that efforts must be made to significantly reduce this. A three-year average currency has been suggested as an attainable goal for ENSDF *if* the evaluation workforce is increased *and* a prioritized plan for mass chain evaluations is developed. Achieving this level of ENSDF currency should be a key priority of the USNDP**.**

The primary way that ENSDF data benefits other nuclear data applications is through its incorporation in the Reference Input Parameter Library (RIPL) form, which is widely used by most nuclear reaction modeling codes. Any efforts to improve the currency of ENSDF should necessarily include the generation and dissemination of updated RIPL files on a regular basis.

Recommendation: We recommend that resources be provided, to improve the currency, consistency, and accessibility of ENSDF and the generation of regularly updated RIPL files.

Impact: An increased frequency of evaluation and a prioritized structure evaluation plan, including the production of regularly updated RIPL files, will ensure that applications reliant on up-to-date nuclear structure information will receive this information in a timely manner. It will also aid in the accuracy of the reaction evaluation process given the role of discrete state data in nuclear reaction evaluation.

2.2 Enhance Reaction Evaluation Capabilities

Issue: Nuclear data users are requesting a more rapid integration of new information into evaluated libraries, posing increased challenges for the ND community to keep pace with the ever-growing body of data and the data needs of users.

Background:
The ENDF/B library provides reaction and decay data for use in modeling and simulation for fundamental sciences (e.g. detection capabilities and detector performance) and applications (e.g. nuclear energy reactors, radiation shielding and dosimetry, nonproliferation and national security). The ENDF/B library is “built-in” to many transport codes such as MCNP, SCALE, OpenMC, Serpent and GEANT4. That means that these codes implicitly assume that the nuclear data files integrated within them reproduce, with fidelity and currency, the known behavior of all relevant nuclear interactions.

Historically, the ENDF/B library has never been fully current with all experimental data compiled in the EXFOR reaction library. The EXFOR library itself does stay current with the flow of reaction experiments published annually. However, the scope of EXFOR has changed several times over the years and many older, but important, data sets have never been compiled. The compilation of experimental data into EXFOR has historically focused on low incident energies, reaching remarkable coverage for reactions with incident neutrons. However, due to expanding user requirements, EXFOR compilation needs to expand to higher energies and different projectiles. Additionally, EXFOR should continue and expand its effort to recover older data sets and embrace the influx of raw and unpublished data caused by the community's increased adoption of the Open Data philosophy (see section 2.13). Another avenue to pursue is to mimic the success of the pre-publication review process adopted in the nuclear structure community, in which a manuscript is reviewed by a data specialist before publication, catching errors sooner and streamlining the process of XUNDL compilation. Similarly, a process could be devised in which experimental work could be reviewed by a nuclear reaction data specialist before publication, enabling quick and accurate compilation into EXFOR.

Modern AI/ML tools, including the development and use of Natural Language Processing (NLP) could shorten the time needed for an EXFOR compilation to be completed by automatically processing tables, graphs, and relevant in-text context. The incorporation of these tools, however, will require new skills not currently present in the EXFOR network. Outdated formats and compilation rules have also substantially hindered the progress of such modern mechanisms. This has motivated the creation of NEA SG-50,[1] which is working to provide a modern interface to EXFOR as well as a framework for providing corrections, both simple error fixes and more complex ones discovered by evaluators in the course of their work.

The ENDF community must also speed up the evaluation process following EXFOR compilation. Doing so presents two challenges: 1) the ENDF libraries were never current or up-to-date with the data available in EXFOR and 2) the scope of data needed by customers is constantly expanding. As an example, the coupling between reaction and structure data leading to accurate gamma cascade data for active interrogation and *(a,n)* safeguards are two recent requests. The Thermal Scattering Law (TSL) library also presents unique challenges due to the number of target materials expanding by an order of magnitude over the past few releases.

Automated evaluation and validation frameworks, with test problems that serve the current customer base as well as emerging customers, would accelerate acceptance of new data.

The ENDF community is strongly leveraged by application-based customers, with the USNDP providing only 15% of the ENDF/B-VIII.0 evaluations. The evaluation effort is, in practice, too large in scope for the USNDP alone. In this sense, the role of the USNDP has been to fill in the gaps. It is unrealistic to expect to address all challenges solely by increasing the workforce. Any expansion must be augmented with an expansion of skills to embrace high-performance computing (HPC), automation, AI/ML, and engagement with the broader community with respect to the needed expertise.

Lastly, Currently ENDF only considers reactions on stable isotopes. As we push the boundaries in our experimental capabilities using facilities such as FRIB, and measure reactions on unstable isotopes that are important across applications (astrophysics, medical, reactor, national security) these should be added to the evaluation process.

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[1] https://www.oecd-nea.org/download/wpec/sg50/

Recommendation: Expansion at the 1-2 FTE level of the USNDP workforce and engagement with members of the broader community is required to ensure the necessary expertise in HPC, automation, and AI/ML. Continued improvements and additional tools should be developed and employed to accelerate EXFOR workflow and compilation.

Impact: Fast turnaround for reaction evaluation decreases the time between an experiment being performed and its data being available to guide evaluation and integration into user codes. This is a "rising tide that lifts all applications" given the central role of reaction evaluation in virtually all of the key nuclear data application areas.

2.3 Maintain Atomic Mass and Nuclear Property Evaluation

Issue: The recommended values for masses and other basic nuclear physics properties are an essential foundation of modern nuclear science. These properties are used in many applied fields and need to be regularly updated as new data become available.

Background: The mass, or binding energy, is a basic property of the atomic nucleus. It determines stability as well as reaction and decay rates. Quantifying the nuclear binding energy, together with systematic knowledge of other fundamental nuclear physics properties such as half-lives, the existence of excited isomeric states and their excitation energies, and spins and decay branching ratios, is indispensable for the study of nuclear structure, stellar nucleosynthesis and neutron-star composition, as well as atomic and weak-interaction physics. Accurate values for these properties and their corresponding uncertainties are also used in other scientific fields, including chemistry, biology, atomic and high-energy physics, as well as in many practical applications of interest to multiple US government agencies. Masses and their derivatives are also of vital importance to the DOE/SC-funded US Nuclear Data Program, since they are directly incorporated into both the ENSDF and ENDF libraries. There is continuing demand for up-to-date and reliable values for these properties for all known nuclei in their ground and isomeric states. The Atomic Mass Evaluation (AME) and the evaluation of basic nuclear physics properties (NUBASE), published as a collaborative effort between scientists from China, Europe, Japan, and US, are the cornerstone mass evaluation efforts [Kon20][2]. More recent efforts also include the development of a global charged-particle decay database[3].

Recommendation: The role of the USNDP in producing these libraries is indispensable and continued support needs to be provided for US participation in these efforts to preserve expertise and continue these activities for the benefit of the science and society.

Impact: The recommended values of atomic masses and other basic physics properties of nuclei are an essential component of accurate reaction rate calculations for all key nuclear data application areas. Continued USNDP participation in the AME and NUBASE collaborations will ensure their continued accuracy.

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[2] https://www-nds.iaea.org/relnsd/nubase/nubase_min.html

[3] https://nucleardata.berkeley.edu/research/betap.html

2.4 Nuclear Astrophysics Evaluation

Issue: Widely-used reaction rate databases for nuclear astrophysics are out of date and the process whereby new evaluations are produced does not consider advances in high performance computing, reaction modeling, covariance treatments, large-scale sensitivity studies, and ML approaches.

Background: Nuclear astrophysics is an interdisciplinary field that uses our knowledge of nuclear science to understand the complexities of stars that are 10^{24} times larger. Using specialized nuclear data sets as input, nuclear astrophysics studies address the sensitivity of billion-dollar satellite telescopes to observe stellar explosions [Lam22], constrain the mechanisms of exploding stars [Gla18], and determine the origin of and abundances of nuclei [Vas22].

The primary nuclear data quantities needed for these simulations include assessments of low-energy p-, α-, n-, and γ-induced reaction cross sections across the entire nuclear chart. Because so many relevant reactions are unmeasured, improved theoretical cross sections are a top priority for these studies. Of special interest are reactions on certain stable and neutron-rich unstable nuclei for studies of the origins of the elements heavier than iron in stellar explosions, which are also required for a range of applied studies including nuclear forensics, nuclear nonproliferation, nuclear energy, and isotope production. Both discrete and quasi-continuum nuclear structure information are also needed, as are the properties of levels near particle thresholds, to indirectly determine unmeasured rates, as well as those of β-decays and β-delayed neutron emission. To advance our understanding of stellar evolution and explosions, cross sections need to be processed into reaction rates so that nuclear data uncertainties can be translated into uncertainties on astrophysical models allowing for robust comparisons between predictions and observations. Sensitivity studies that identify the most impactful reactions for future investigation are critical, as is the development of software tools, methodologies, and databases to store, process, manipulate, and utilize nuclear data sets to determine their ultimate science impact.

Recommendation: A coordinated 1-2 FTE level expansion of the USNDP workforce should be made to improve evaluation and modeling of astrophysical reaction rates involving researchers with appropriate expertise at both the national laboratories and associated universities.

Impact: Sufficient investment in nuclear astrophysics would improve our understanding of the origin of the elements in cosmic settings, help decipher stunning new observations including neutron star mergers such as [Kli21] in this new era of "multi-messenger astronomy" [Die22] and enable the full scientific impact of FRIB measurements involving nuclei far from stability.

2.5 Develop Statistical Nuclear Structure Data Evaluation and Databases

Issue: All nuclear reaction evaluations requires accurate, continuously updated, statistical nuclear structure data, including nuclear level densities (NLD), photon strength functions (PSF) and optical model (OM) parameters. However, while a wealth of new statistical nuclear data are being generated, there is currently no ongoing effort to compile or evaluate NLD and PSF data.

Background: At low excitation energies (≈1-3 MeV), the properties of discrete levels are incorporated in the Evaluated Nuclear Structure Data File (ENSDF). Above these energies, average level properties of heavy nuclei are described by two statistical probability distribution functions: the nuclear level density (NLD) and the photon strength function (PSF). Along with the NLDs and PSFs, nuclear reaction evaluations for heavy nuclei also use phenomenological optical models (OM) that describe the scattering, emission and absorption of particles by the nucleus. The growing importance of these properties is evidenced by a doubling in the number of recent publications in both theory and experiment mentioning them since 2010. In recent years, new approaches for NLD and PSF measurements have been developed that can be used at radioactive beam facilities [Spy14, Wie21], indicating that new results can be expected from FRIB and similar laboratories in the near future. Similarly, RIB facilities are expected to provide new data for OM on unstable nuclei. A recurring theme in most of the NSAC-ND subgroups is the need for a robust, recurring evaluation mechanism that incorporates the new influx of NLD and PSF data from statistical γ-ray sampling methods following direct reactions, β-decay, and particle evaporation spectral measurements to support robust, physically defensible nuclear reaction modeling.

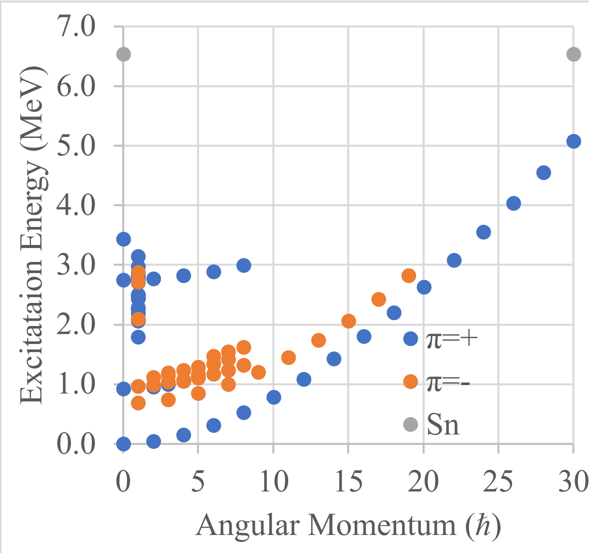

Figure 2.1: Known positive and negative parity states in ^{236}U. The neutron separation energy is indicated by the two points at 6.5 MeV.

While there is a robust, ongoing, evaluation effort for discrete states in ENSDF, there is no equivalent effort in place for statistical quantities. Figure 2.1 shows the excitation energy and angular momentum of excited states in ^{236}U from ENSDF, which is perhaps the most important nucleus for nuclear energy, national security and nonproliferation. The figure highlights the fact that no nuclear data information is provided for the states in the vicinity of the neutron separation energy that are populated in neutron-induced reactions. Evaluated data addressing NLD, PSF and OM potentials are required to fill this gap.

The International Atomic Energy Agency (IAEA) led a coordinated research project (CRP), that included USNDP participation, to establish a recommended PSF database [Gor19]. However, there is no continuing plan to incorporate NLD, PSF or OM data produced by FRIB or other stable and radioactive ion beam facilities.

Recommendation: A TNDC should be formed to develop and maintain a regular evaluation process for statistical nuclear structure data. The USNDP should provide at least 2 FTE to the TNDC to measure and evaluate statistical data at FRIB and other domestic and international facilities. This effort should be coordinated with international efforts, such as the Reference Input Parameter Library [Cap09] to ensure consistency. Up to 3 years could be required for training and/or recruitment of both researchers.

Impact: Regularly updated databases of statistical nuclear data would improve models of astrophysical nucleosynthesis and aid in the modeling of nuclear reactions for national security and nuclear energy applications. They would also enhance the interpretation of signals from neutrons and gamma active interrogation systems used in nonproliferation and planetary neutron spectroscopy. Lastly, they would help lower costs for neutron shielding for fission and fusion energy systems through improvements to neutron transport modeling.

2.6 Establish Methods for Continuous Fission Evaluation

Issue: There is a crosscutting need for persistent evaluation of fission data, including reaction mechanisms, formation and decay of the compound state, and decay products.

Background: Fission is a complex phenomenon that remains at the forefront of cutting-edge scientific research. Fission touches many application areas including nuclear energy, criticality safety, nonproliferation, nuclear forensics, and stockpile stewardship. Each application area may have different nuclear data needs and priorities, but all require regularly-updated fission evaluations which, in turn, rely on measurements and model calculations. Each of these must be continually updated in response to user needs.

Reliably measuring fission observables at the high accuracy required by applications is a challenge. High-precision measurements of prompt fission neutron spectra (PFNS) (below 2% uncertainty) [Kel20, Mar20], (n,f) cross sections [Sny21] (around 0.1%), and $\overline{\nu}$ [Mar22] (around 0.8%) took a decade of research. These efforts established new measurement skills and improved understanding of the data. Prompt fission neutron spectral (PFNS) measurements with the ChiNu array on major actinides (^{235}U [Kel22] and ^{239}Pu [Kel20]) have filled some gaps, including new measurements at the thermal point, important for reactor applications. However, most of the data are only available for certain isotopes over a small energy range. While there was an updated $\overline{\nu}$ evaluation for spontaneous fission in 2008 [San16], there has been no similar suite of measurements for neutron-induced fission from thermal to 20 MeV. The quality of fission cross section data for major actinides in the fast energy range is generally sufficient for many applications, but minor actinide data can be discrepant [Tov10, Par82, Bel12].

Turning measurements into evaluations requires a consistent framework across a broad energy range for major and minor actinides for both neutron and gamma observables. The available measurement precision, with sub-percent level uncertainties for the PFNS, fission cross sections, and ν spectra for major actinides, cannot be matched by fission models. On the theory side, fission event generators were developed in the last decade that have made it possible to simultaneously simulate the PFNS and ν and couple them to gamma observables [Bec13, Ver18, Lit16, Sch19] and new computation platforms using GPU-capabilities are expanding the modeling fidelity. The uncertainties inherent in these models remain larger than the experimental data that they simulate, and additional measurements are still needed. For example, extracting a range of realizations of ^{252}Cf fission from data on fragment yields yielded an uncertainty on $\overline{\nu}$ larger than that on $\overline{\nu}$ itself by a factor of several [Ran19]. Integral experiments being designed to tease out compensating errors [Hut22], or to be as similar as possible to an application of interest [Sie21, Mic21], would provide guidance to these modeling efforts. A broad integral and differential experimental analysis of ^{238}Pu-^{242}Pu by Neudecker [Neu21] showed shortcomings at thermal, resolved and unresolved resonance energy regions, and the fast neutron range up to 2 MeV.

Consistency between fission observables, like $\overline{\nu}$ and the PFNS, but also the prompt fission gamma spectra (PFGS), average gamma multiplicities, and gamma and neutron multiplicity distributions, would be desirable where models agree with experimental data. Further model development and validation will be needed for these observables, along with validation of basic physics data such as the fragment yields, $Y(A)$, and total kinetic energy (TKE). It is worth noting that the PFNS remains a challenge for the fission event generators. The ChiNu PFNS measurements [Kel20, Kel22] of fission neutron spectrum, semi-integral data [Dan18, Tho18], as well as measurements of $\overline{\nu}$, TKE, $Y(A)$, and the PFGS are indispensable for improving fission models. In the past, many of these quantities have been evaluated independently. However, new complete event fission models combine these disparate pieces and improve evaluations. Incorporating such models into evaluations will be an important part of any persistent fission evaluation effort.

It has been repeatedly shown that relying only on k_{eff} for adjusting libraries leads to compensating errors between nuclear data, *e.g.,* changes in the ^{235}U PFNS are compensated by changes to the ^{235}U capture cross section and ν in the resonance region [Cha18]. However, using different integral responses [Alw22, Gro22] allows orthogonal views of the same nuclear data and thus provides better constraints on these data. Expanding validation and adjustment suites with observables such as reaction rates, reactivity coefficients, pulsed sphere spectra, criticality, and β_{eff} would be highly beneficial. Recently, integral experiments were recently designed [Hut22] using AI/ML techniques to help resolve compensating errors. If this method of experiment design is successful, such approaches should be further investigated and implemented in the design of new experiments. AI/ML techniques will be crucial for optimizing experiment design, introducing large-scale nuclear data validation feature analyses, and emulating fission-event generators [Hut22, Sie21, Neu21, Whe20].

Finally, the required accuracy of fission evaluations and the priority with which they are addressed should come from applications. In most cases, a good evaluation cannot be made better without additional experimental data. Thus persistent, ongoing fission evaluations must include a measurement program as well as updating models based on the measurements.

Recommendation: A TNDC should be formed and periodically updated to provide recommended nominal values and associated uncertainties for the ever-growing body of correlated fission data including reaction cross sections, independent and cumulative fission product yields and neutron and gamma-ray energies and multiplicities. A permanent 2 FTE expansion of the USNDP workforce should be supported at appropriate locations where experimental and modeling work is being performed. Training should proceed fairly quickly for the researchers who participated in the NDIAWG-funded fission activities over a 2 year period.

Impact: The data from a fission TNDC would reduce cost and enhance safety in the next generation of advanced nuclear reactors, increase confidence in the safety and reliability of the nation's nuclear stockpile and nonproliferation efforts, and provide much-needed information for the development of both phenomenological and microscopic fission theories.

2.7 Targeted Accelerated Decay Data Evaluations

Issue: Rapidly updated, correlated, decay data for certain key nuclides is needed for numerous applications.

Background: At first glance most of the application needs listed in section 4 of the first report involve reaction data. However, decay data, particularly for select isotopes near stability, are critically important to virtually the entire application space. While their importance for medical applications is clearly spelled out with regard to patient dose and imaging requirements in section 4.3 of the first NSAC-ND report, this class of nuclear structure data also underlies most of the other applications:

- Energy (section 4.2 of the first NSAC-ND report): decay heat, decay constants and branching ratios for specific materials;
- National Security (section 4.4 of the first NSAC-ND report): interpreting data from detectors and instruments;
- Nonproliferation (section 4.5 of the first NSAC-ND report): decay data for forensics, safeguards, detector characterization, emergency response, and fissionable materials production detection;
- Space Applications (section 4.6 of the first NSAC-ND report): planetary nuclear spectroscopy, space reactors and space-based nuclear detonation detection.

In addition to these connections to applications, decay data plays a central role in supporting basic science as expressed by the Nuclear Data Needs and Capabilities for Basic Science summary statement reproduced in section 4.1 of the first NSAC-ND report.

Decay data are also related to several USNDP efforts outside their standard structure evaluation activities (see sections 2.1.5, 2.1.11 and 2.2.3.2 in the first NSAC-ND report), demonstrating their general importance.

ENSDF contains 220 mass chains comprised of roughly 3,300 nuclides, requiring 15-18 years for a complete update given a publication rate of approximately 12 mass chains/year. As a result, on average, incorporation of any published nuclear structure data takes more than 8-9 years. A similar time scale applies for the adoption of any new policies adopted by the international Nuclear Structure and Decay Data (NSDD) network. While this pace may be adequate for most nuclei, a faster approach to updating targeted decay data in the ENSDF database with high priority to specific applications would serve the community better.

The current USNDP workforce cannot update all the published/incoming data immediately upon publication. However, prompt consideration of nuclide evaluations related to decay data for the ENSDF update could he performed for high-priority nuclides mentioned in the first NSAC-ND report listed above. Such an effort would also help accelerate subsequent ENSDF evaluation process for these nuclides.

Recommendation: A panel of subject matter experts from all application areas is convened to annually to update a list of key decay data. At least one additional 1 FTE should be added to the USNDP, perhaps spread over multiple application locations, to provide for the rapid inclusion of new decay data outside of the regular nuclear structure evaluation process, and to perform any required measurements. These data should be made available in both a stand-alone library as well as being incorporated into each nuclide evaluation at its next update to ENSDF. Approximately 3 years would be required to recruit and train the new evaluator.

Impact*:* The acceleration of decay data evaluation for targeted nuclides would improve the interpretation of forensics data for nonproliferation, decay measurements for novel reactor design, and determination of dose for medical applications. It would also aid in subsequent nuclear structure evaluation efforts in support of ENSDF.

2.8 Provide Comprehensive, Consistent Neutron Reaction and Structure Data

Issue: Measurement, compilation, evaluation, and dissemination of neutron-induced data is needed in support of a wide array of applications, particularly in the nuclear nonproliferation and energy application space. However, due to its central role in many applications, including basic applications such as nuclear astrophysics, neutron-induced reaction and structure data are rapidly produced, often leading to significant inconsistencies in the data.

Background: Perhaps the most well-established example of crosscutting nuclear data is data related to neutron-induced reactions. There are more than four times as many (n,x) than (p,x) evaluations, highlighting the importance of neutron-induced reactions for nuclear energy, defense and nonproliferation applications, and the correspondingly larger historical support for both neutron-induced measurements and evaluation efforts. While other evaluation efforts exist that cover a wider range of projectiles, such as the TENDL library[4], these efforts represent only a small fraction of the attention given to neutron-induced reactions given the disproportionate number of experimental data sets available in EXFOR for neutrons (11,219) relative to protons (4883). Furthermore, the lack of a Coulomb barrier means that (*n,x*) data exist well into the resonance region for all nuclei, in contrast to charged particle-induced data.

Signatures of neutron-induced reactions are key for nuclear nonproliferation and security applications in addition to fossil fuel and space exploration. In most applications neutrons are born at high energy, e.g., 14-MeV source neutrons in T(D,n)α reactions or 2 MeV (on average) in a fission environment. In these cases, the incident neutron often undergoes several mean-free path interactions (neutron scattering) prior to absorption, leading to a broad range of neutron energies whereupon interpretation requires high-fidelity nuclear data. Other than elastic scattering, all other neutron interactions leave the (bombarded) residual nucleus in an excited state which can then decay by particle emission or electromagnetic emission or both. When gamma rays are emitted in neutron-induced reactions, their energies are equivalent to the unique recoil-corrected energy difference between initial and final states of the associated transitions. Accordingly, the produced pattern of emitted gamma rays provides distinct fingerprints of isotopes present in an unknown assembly and are thus particularly useful for nondestructive-assay (NDA) applications. To ensure all key applications listed in the first NSAC-ND report are adequately accounted for, neutron interactions at nearly all energies from 20 MeV down to thermal must be included.

The large quantity of (*n,x*) reaction data may give an impression of robustness. However, there are large gaps that have figured prominently in recent NDIAWG- and NA-22-funded efforts, including consistency in (*n*,γ) and (*n,n'*γ) data, where correlated *n*-γ data from the latter are particularly deficient. These data are also critical for reaction modeling since the broad range of states populated in (*n,x*) reactions provides critical insight into nuclear level densities and photon strength functions (see section 2.5).

The current ENDF reaction database stores discrete reaction information, but in some instances databases with less specific reaction and products would be beneficial. For example, accurate measurements of (n,xγ) have been performed, where the reaction products are measured without specificity to the reaction channel or excitation state of the compound nucleus. One example is the Evaluated Gamma-ray Activation File (EGAF) library [Fir14] where gamma-ray productions are compiled relative to the total radiative thermal neutron- capture cross section. New methods for extracting and using data in the database (e.g. pyEGAF [Hur23]) can be used to identify where new measurements or theories are needed to fully describe the primary gamma-ray decay scheme. Gaps have been identified for fission-product nuclides with large total neutron-capture cross sections and yields that may affect decay-heat calculations. Use of such non-differential data may directly impact application needs as well as help guide future targeted experimental campaigns to address the gaps in the data. This is particularly apparent and important for fission-product nuclides, especially those with large total neutron-capture cross sections and fission-product yields, as this has implications on decay-heat calculations and may help guide future targeted experimental campaigns to address the gaps in the data.

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[4] https://tendl.web.psi.ch/tendl_2019/tendl2019.html

There is significant evidence that the non-selective nature of (*n,n'*γ) data is particularly useful for improving ENSDF evaluations, with early work by Demidov [Dem04] and more recently from Fotiades [Fot10] showing the utility of these data for determining off-yrast structure. The value of these data has led the USNDP to pursue several nuclear data efforts, including the Evaluated Gamma Activation File (EGAF) database[5] [Fir14], the CapGAM library[6] and most recently the Baghdad Atlas [Hur21]. Additional databases compiling (n,n'γ) data with different neutron sources, including most notably for 14.1 MeV "DT" neutrons.

Recommendation: A TNDC should be formed with participants from the national security, nuclear energy and nonproliferation communities to ensure that all of the existing (*n,x*) databases are regularly updated with new data as it becomes available, and to determine the need for new (*n,x*) benchmark data sets. The TNDC should include additional support at the 1 FTE level for USNDP researchers to ensure integration of new data into the nuclear data pipeline. Given the importance of DT neutrons to fusion, national security, nonproliferation, and planetary nuclear spectroscopy an additional 1 FTE USNDP effort should be provided to enable the development of a 14 MeV complement to the Baghdad Atlas [Hur21]. Given the large number of researchers engaged in these application areas recruitment and training should take no more than 2 years with the possibility of the first researcher starting in year 1.

Impact: A persistent and coordinated effort to regularly improve and update (*n,xn*γ) data would have far-reaching consequences for virtually all of the applications listed in the entire first NSAC-ND report, including national security, nonproliferation, fission and fusion reactor design and planetary nuclear spectroscopy.

2.9 Charged-particle stopping powers measurement and evaluation

Issue: Poorly quantified stopping powers have led to a lack of predictive capabilities for space exploration, ion beam therapy, and the development of detectors for numerous applications.

Background: Significant uncertainties exist in stopping powers for light- to heavy nuclei. Well benchmarked charged particle stopping powers (*e.g.*, dE/dx) are critical for a wide variety of applications ranging from modeling single event effects (SEE) and human dosimetry calculations for space exploration; fission and fusion materials damage; Ion Beam Therapy (IBT) and optimized isotope production; scintillation physics; as well as detector modeling for basic science, national security, and nuclear nonproliferation. These needs have been well documented at a number of WANDA workshops, including the materials damage session at WANDA 2019 [Ber19]; the detector modeling session at WANDA 2020 [Rom20]; the space applications session at WANDA 2021 [Kol21]; and most recently in a dedicated stopping power session at WANDA 2022.

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[5] https://www-nds.iaea.org/pgaa/egaf.html

[6] https://www.nndc.bnl.gov/capgam/

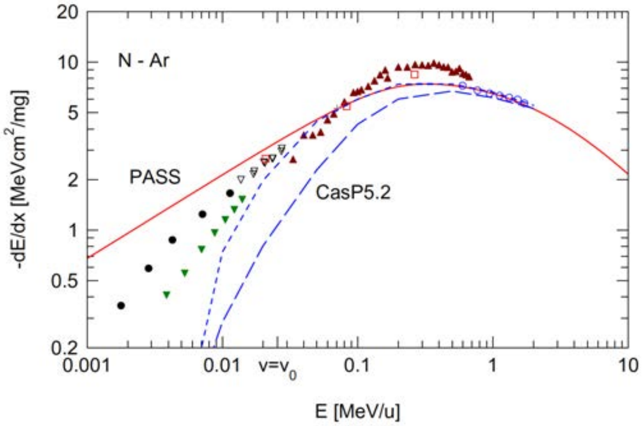

Figure 2.4: Experimental data on stopping powers for nitrogen on argon compared to predictions from the PASS and CasP5.2 codes [Sig02].

Uncertainties in stopping powers introduce covariances into measured and modeled nuclear data quantities that are most relevant to these applications, but this document will concentrate only on the quantities that introduce uncertainties into the calculations of stopping powers themselves. The work by Sigmund [Sig16] shows that the largest uncertainties on dE/dx are for the lowest relative velocity of the ion, referred to as the Bragg Peak, where theoretical models manifest the greatest difference, and guidance from experiment is most often lacking. Modern dE/dx models introduce missing physics, including atomic excitation of both the beam and the material, but require experimental data for adjustment. An example from Ref. [Sig16] for nitrogen ions on argon using two modern models, the Binary Theory [Sig02] used in the PASS code and PCA/UCA [Sci99] used in the CasP5.2 code, together with the experimental data available for the system, is shown in Fig. 2.4 above. Any optimization of the parameters in stopping power models clearly requires guidance from experiment at low energies per nucleon.

The need for improved experimental data is particularly evident for SEE and IBT where high dose density is of the greatest concern. Alterations of stopping powers can cause huge changes in the location of the Bragg peak near the end of particle trajectory where the Linear Energy Transfer (LET) is highest. In the case of materials damage in fission and fusion power systems, a wider range of stopping powers is of interest since reaction channels for a large variety of recoil and ejectile energies contribute to the total cross section of displacements per atom (σ_{dpa}); gas production in reactor pressure vessels and tokamaks; and energy deposition in inertial confinement fusion plasmas.

This lack of data was well summarized in the talk given by Claudia Montanari at WANDA 2022. Figure 2.5 presents a figure from Montanari's talk showing how many proton stopping power data sets exist for elements across the periodic table.

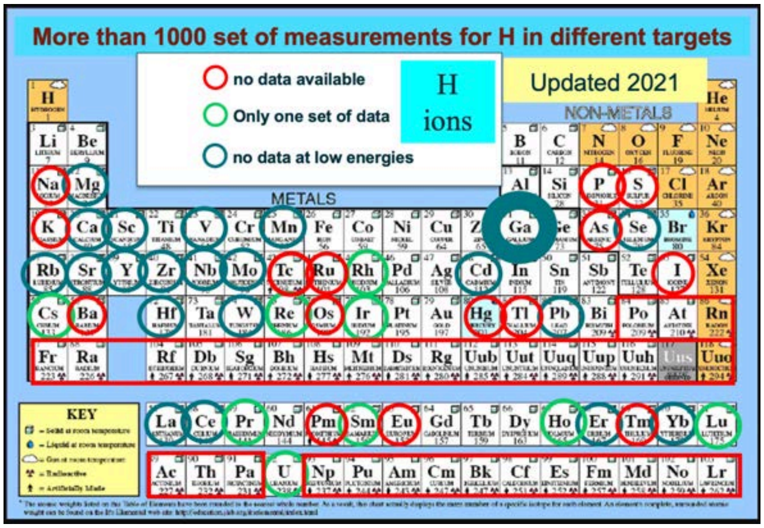

Figure 2.5: Stopping power data sets for protons in different elements from the talk by *Montanari* at WANDA 2022. Limited-to-no data exists for several elements used in semiconductors (Ga, As & Se), detectors (Ba, I, K, Na) and shielding (Pb) and isotope production (Tl), and both fission (Zr) and fusion (Nb) applications.

Recommendation: A TNDC should be formed including representatives from the space exploration, fusion energy, ion-beam therapy, and detector design communities together with a new USNDP staff member to develop a plan to perform the required experiments, modeling, compilation, and evaluation of charged-particle stopping powers for targeted light-through mid-mass nuclei. Recruitment and training can be expected to take 3 years, starting with an upper level graduate student candidate. Further effort may be required as well to develop an appropriate modeling and evaluation procedure for this type of data.

Impact: Improvements in stopping power data will improve the design of radiation-hardened electronics for space exploration, aerospace, and fusion energy applications. It will also aid in the development of improved ion beam therapy applications by maximizing dose at the targeted location while minimizing damage to adjacent tissue. These data will also aid in the design of detectors, analysis of detector response, and detection efficiencies for a broad array of experiments, which underpin many of the nuclear data needs noted throughout this report including charged particles, fission products, neutrons and gammas.

2.10 Comprehensive reaction measurement and evaluation to *E/A*≤10 GeV/amu)

Issue: Incomplete compilation, evaluation and dissemination of nuclear reaction data has led to a lack of predictive capabilities for many applications. This lack has had particularly significant impact on applications involving charged particles and projectiles with energies well above 20 MeV/amu such as space exploration, ion beam therapy, and accelerator-based isotope production.

Background: Traditionally, nuclear reaction evaluation efforts have focused on neutron-induced reactions with projectile energies ≤ 20 MeV. This reflects the importance of neutrons from the DT reaction, including reactions involving energetic deuteron and triton projectiles in high energy density plasmas relevant to national security and nonproliferation applications. Reaction cross sections at these energies, on all but the lightest nuclei, are best described using statistical models that employ Hauser-Feshbach formalism [Hau52] with direct reactions playing a more limited role, particularly in heavier nuclei. Pre-equilibrium reaction modeling also plays a role at higher energies but is of relatively limited importance, particular for energy applications.

Unfortunately, while the entire application community relies on up-to-date nuclear reaction models, reaction code development is not a burden shared by the entire community. Although there are individual efforts, such as the Talys package [Kon05, Kon12], CoH [Kaw10], EMPIRE [Her07], YAHFC [Orm21], CGMF [Tal14], much of this effort lacks coordination. A concerted, consistently funded effort between all of the principal theorists, modelers and code developers is clearly needed for reaction modeling at all incident particle energies.

Most recently, high-energy ($E/A \leq 10$ GeV/amu) projectile reactions have emerged as a new crosscutting area of importance for both isotope production and ion-beam therapy under medical applications and space radiation protection for both astronauts and electronics. The addition of high-energy reaction evaluations to the USNDP mission is likely to present the greatest challenge to the nuclear data community. As the projectile energy increases, the number of open channels, and thus unconstrained model parameters, explodes, challenging traditional uncertainty quantification methodologies. At even higher energies (~ 200 MeV/amu), mesons are produced, and it makes more sense to model reactions using an inter-nuclear cascade code. The wide energy range represented by these reactions and the mismatch between the expertise of the members of the nuclear data community, who tend to come from low-energy nuclear science and engineering disciplines, will be a continuing challenge. Because particles produced in the cascade initiated by the reaction are eventually stopped in matter, the full benefit realized by improved nuclear reaction data at higher energies requires corresponding improvements in ion stopping powers (described in section 2.9).

Nuclear data at high energies was the topic of one of the sessions at the WANDA meeting in 2022[7]. Compilation and evaluation of this high energy nuclear data is particularly important for space exploration due to the harmful effects of the interplanetary radiation environment. The wide range of energies, up to the TeV scale, and species, $1 < Z < 28$ of galactic cosmic rays (GCRs) [Bad92], make it challenging to determine all the potential effects on spacecraft and astronauts. While the Earth's atmosphere has a protective effect, cosmic ray showers reach the ground all over the Earth and, in fact, have been studied using collider detectors. Muons from cosmic rays pass all the way through these detectors, producing tracks perpendicular to those from beam-beam collisions and are present even when the beam is not on [Gru03, Rid05, Ach04, Ada16]. The ALICE detector at the LHC includes the dedicated cosmic ray detector ACORDE [Fer07], used in the analysis of Ref. [Ada16]. Collisions of GCRs with nuclei in the Earth's atmosphere or a spacecraft in orbit can generate showers of particles, including pions, muons, neutrinos, electrons, and photons as well as protons and neutrons.

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[7] https://conferences.lbl.gov/event/880/

The penetrating power of the initial GCRs and the secondaries generated by their interaction with matter can have a serious impact on the safety and viability of space exploration. The 1% of GCR primaries heavier than He nuclei can be especially serious because the damage they inflict scales as Z^2. The secondary particles generated from GCR interactions with spacecraft material [Fin18] such as aluminum, polyethylene, and composites can harm astronauts and disrupt or disable electronic systems. The spacecraft shielding designed to reduce the GCR flux is also a target that can increase the secondary flux. Because of the wide variety of possible shielding materials and thicknesses, modeling is essential to determine the sensitivity of the secondaries (both in flux and composition) to different shielding configurations, as well as to determine the subsequent harmful impact of those secondaries on electronic systems [Hoe20] and humans [Dur11].

Understanding the effects of the highest energy GCRs requires high energy (GeV/amu range) nuclear data and modeling. However, there are no measurements for incident projectile energies greater than 3 GeV/amu. There is a possibility to fill part of these critical gaps in nuclear data employing fixed-target collisions at RHIC. A beam use proposal was recently made to bombard C, Al, and Fe targets with C, Al, and Fe ions at energies from 5 to 50 GeV/amu and measure the produced secondaries using the STAR detector. This measurement, however, would have to be completed before RHIC is shut down and the conversion of the facility to the Electron-Ion Collider begins in approximately 2025.

Given the lack of data at the appropriate energies, simulations of space radiation effects have large uncertainties. The space research community has generally relied upon phenomenological nuclear reaction models such as the Double Differential Fragmentation model (DDFRG) [Nor21]. Many of the models rely on abrasion-ablation models [Huf75, Wer21] or semi-empirical parameterizations [Luo21]. Researchers modeling these interactions could benefit from codes developed to study data from RHIC. The use of hadronic cascade models such as the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) code [Ble99], which was shown to be able to predict proton and deuteron yields from the BNL Alternating Gradient Synchrotron studies of 15 GeV protons on Be and Au targets [Som19, Abb92], could significantly advance simulations of collisions relevant for space exploration. For further information about nuclear data needs for space applications, see Refs. [Kol22, Smi22].

Recommendation: A TNDC should be formed including representatives from the space exploration community, the DOE Isotope Program, the medical applications, and the intermediate energy nuclear physics community to develop a plan to extend nuclear reaction evaluations to include projectiles with energies up to several GeV/amu. The plan would include an integrated program that includes targeted experiments, modeling, compilation, and evaluation. A new modeling effort that draws on data in existing repositories such as HEPData[8] [Mag17] as well as acquiring its own data at appropriate DOE-NP facilities, such as the STAR detector at RHIC is necessary. An additional 2 FTE USNDP workforce working in collaboration with non-USNDP experimental teams would be required. Training and/or recruitment could take 3 years or more.

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[8] https://www.hepdata.net/

Impact: Improvements in high-energy reaction modeling will improve the design of radiation-hardened spacecraft for space exploration and aid in the efficient, contaminant-free production of radionuclides for use in medical applications and environmental monitoring.

2.11 Provide Nuclear Data for Fusion Energy

Issue: There is a lack of both differential and integral nuclear data needed for the development of fusion energy system, including low-energy thermonuclear reaction data, in-line tritium breeding, and high-energy neutron-induced reaction data for shielding and damage studies.

Background: In December 2022, DOE announced that the National Ignition Facility (NIF) had achieved ignition, i.e., the energy produced via thermonuclear fusion exceeded the laser energy used to drive the capsule implosion. This result followed relatively quickly on the heels of the first observation that Lawson's criterion was exceeded in an inertial fusion experiment [Abu22]. The onset of repeatable, high-yield shots at the NIF opens a new avenue of fusion research that could potentially lead to a new, carbon-free, energy source.

The development of both inertial and magnetic confinement fusion (ICF and MCF) systems hinges on the ability to accurately model a complex system whose properties depend on a plethora of atomic, nuclear, and plasma physics data. Some of these needs, such as a detailed knowledge of thermonuclear and neutron-induced tritium production reactions are common to both. Others, such as understanding neutron-induced damage cross sections on normal or superconducting magnets and final-stage optical materials, differ between the two modalities.

Some of the nuclear data needed to model materials damage, parameterized as the cross section for displacements per atom (σ_{dpa}) and gas production [Zin14] for fusion energy systems were identified in the session on materials damage at WANDA 2019 [Ber19a]. There has been a relatively modest effort to address nuclear data needs for fusion energy as compared to the other needs identified in nuclear energy. A fusion evaluated nuclear data library (FENDL) was prepared in 1994 [Saw94], which exhibited differences in structural materials σ_{dpa} and He production of 9% and 18% respectively relative to ENDF.

The top priority need identified at WANDA 2019 was for high-energy (up to 14 MeV) neutron data and benchmarking facilities. The lack of such a capability led to *ex situ* studies using lower energy reactor-based neutron sources as well as surrogate studies using charged-particle beams with significant uncertainties. The use of these alternate sources are particularly concerning in the case of next generation High-T_c superconducting materials planned for use in MCF systems, such as REBCO [Fis18], where prompt damage could potentially cause the magnet to quench.

It is worth noting that the fast neutron data needed for fusion energy development has a great deal of overlap with both national security and space applications, offering the opportunity to address some of these needs collaboratively.

Recommendation: Two TNDCs should be established to identify and address outstanding nuclear data needs for inertial confinement and magnetic confinement fusion research. These

TNDCs should work collaboratively to address shared nuclear data needs through a combined program of targeted evaluation and measurement. Integral benchmark testing of critical materials should be conducted using high-intensity neutron sources with energies up to 14 MeV. Additional support is needed for equal participation by the USNDP in these TNDCs at the 0.5 FTE level each for 3 years to assess nuclear data needs and perform collaborative measurements with federal and non-federal sponsors. An ongoing 0.5 FTE effort would ensure that new integral data are taken into account as they become available.

Impact: Improved nuclear data will help expedite the development of fusion energy systems and complementary applications, including the modeling of neutron-induced dose for space applications and national security efforts.

2.12 Continue Development of Modern Data Formats

Issue: Legacy nuclear data formats limit opportunities for automation and innovation enabled by modern artificial intelligence and machine learning (AI/ML) tools.

Background: The nuclear data formats used in the ENDF, ENSDF, EXFOR and Nuclear Science References (NSR) libraries were originally designed in the 1960s for punch-card readers and FORTRAN codes. These legacy formats define the ontology of nuclear data and because they are difficult to modify and extend, essentially locking developers into a 1960s mindset of data and their interrelations. This not only slows development of the field, but also presents a sizable barrier to new entrants in the field as they struggle to understand both the obsolete formats and the associated codes.

In 2016, an NEA WPEC Expert Group was established to develop and maintain a hierarchical and Object-Oriented Program (OOP)-friendly evaluated reaction format called Generalized Nuclear Data Structure (GNDS). This format was designed so that data can be serialized into JSON, XML, or other hierarchical data formats. More importantly, the reaction ontology maps simply onto the physics model used in nearly all neutron transport codes. CSEWG, the collaboration that develops the ENDF/B library, is midway through the transition from the legacy ENDF format to GNDS.

Given this success, the DOE has funded a similar 3-year modernization project for the ENSDF nuclear structure library. This project will deliver a hierarchical format for ENSDF and supporting APIs. Similarly, the IAEA is transitioning the experimental reaction data format for EXFOR to JSON. More promisingly, the NEA has formed a WPEC Subgroup, SG-50, to develop recommendations for extending the EXFOR format to include unique metadata identifiers and post-compilation comments and corrections. While this provides an excellent foundation, additional support will be needed to implement the SG-50 recommendations and fully realize this vision. Further, the NSR format and library has yet to initiate a dedicated modernization project.

Other databases recommended in this report, such as astrophysics (Section 2.4), statistical decay properties (Section 2.5), non-differential neutron data compilations (Section 2.8), and stopping powers (Section 2.9) should also follow a standard structured format similar to GNDS for ease of access and tool development. Other existing databases, such as the NSR, should also be modernized. These modern database structures and analysis tools provide an opportunity for connections with data scientists beyond nuclear science and a rich resource for new techniques in data science.

Recommendation: New, sustained investment at the 0.5 FTE level in modern hierarchical, OOP-friendly, nuclear data formats and APIs to enhance accessibility, usability, and lay the groundwork for an AI/ML integrated compilation, evaluation, and dissemination platforms. Recruitment should take place within a single year since there was a recently-funded NDIAWG project along these lines

Impact: Modern data formats and APIs improve data transparency, accessibility, and usability; mitigate against disconnected data silos; and facilitate integration of AI/ML and other tools into the nuclear data pipeline.

2.13 AI/ML for Modern Nuclear Data Compilation, Evaluation, and Dissemination

Issue: The increasing volume and rate of information poses significant challenges to continued effective nuclear data compilation, evaluation, and dissemination— a challenge that can be partially mitigated via the application of AI/ML techniques.

Background: Modern nuclear physics experiments can result in the production of extremely large, information-rich data sets. This, combined with the high and increasing rate of published nuclear data products in academic journals, poses a growing challenge for continued effective stewardship of nuclear data. According to recent estimates, about 2.5 million articles are published each year in academic journals around the world, with numbers growing about 3 percent per year. For academic journals featuring nuclear data products, more than 4,000 articles were published in 2020 alone [Fyf20, War18, SCI21]. In recent years, AI/ML tools have emerged that can help to tackle these challenges through enhanced nuclear data compilation, evaluation, and dissemination [Boe22]. These opportunities were highlighted in a report [Sob20] arising from the 2020 WANDA Workshop and a recent review article on current nuclear data needs [Kol22].

Data compilation requires, as a first step, collection of the relevant literature and extraction of the experimental data. In addition to ad hoc literature searches and PDF manuscript databases [Zer22], researchers and evaluators largely turn to the NSR database hosted by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory (BNL) to identify and process nuclear data literature [Pri11]. This platform, a critical resource for the nuclear science community, is heavily reliant upon human intelligence tasks, and thus time- and resource-intensive to maintain. Entity recognition combined with AI via natural language processing (NLP) offers a means by which keywording for nuclear data literature compilation can be accomplished in a more automated fashion. For example, the NucScholar project led by Lawrence Berkeley National Laboratory (LBNL) showcased a demonstration of automated bibliographic compilation using text, LaTeX, and PDF parsing and the use of NLP for categorization of literature (*e.g*., experiment vs. theory, nuclear reactions vs. structure, *etc.*) [You22]. The BNL team has also demonstrated the capability to detect and decompose tabular information in documents for further processing. This is emblematic of a critical step in an ML-enhanced data compilation life cycle, from extraction of the data and its conversion into an ML-compatible format to the use of these data in traditional and ML-enhanced evaluations. While the value of these tools has been demonstrated within the USNDP, significant additional effort is needed to complete the software development life cycle, including fine tuning algorithm designs, implementing a coherent framework, and testing and integrating with existing NNDC tools.

Data dissemination is primarily focused on how to best push the data out to users. This is typically accomplished via a web interface (or in the future, an app) backed up by a database. AI/ML tools can also help to promote intelligent data dissemination by improving user interaction and experience through natural language queries. For example, Google recently open sourced the BERT model [Dev18], which provides word embeddings pre-trained using the Wikipedia corpus and an unsupervised NLP technique that uses bidirectional encoder representations from transformers. This extremely powerful language representation model provides a basis for training state-of-the-art question answering systems using small batch fine-tuning (*i.e.*, a nuclear physics specific natural language question answering model). The NucScholar team has demonstrated fine-tuning of BERT for the nuclear physics lexicon, which provided a significant improvement in generating nuclear-physics-specific search queries. These capabilities, applied to data dissemination, have the potential to greatly improve access to accurate, reliable nuclear data for a variety of federal missions, including nonproliferation, nuclear forensics, homeland security, national defense, space exploration, nuclear energy, and scientific research.

AI/ML tools also have an important role to play in nuclear data evaluation. Traditionally, data evaluation is performed by an evaluator’s assessment of experimental data along with the use of physics-based model codes to provide recommended values that best represent present-day understanding of the physical quantities of interest. However, in the case of disagreement between experimental measurements, lack of empirical data, and/or incomplete theoretical descriptions, evaluators must make decisions in the absence of full information. To assist in obviating the biases and errors associated with human decision making, physics-informed ML can be used to predict missing data, identify problematic data sets, or enhance reaction modeling codes for improved evaluation. In the case of reaction modeling, this is accomplished by adapting the loss function for neural network model training to include both physics constraints and a standard loss term representing experimental data trends [Kar21]. If a full theoretical description is available, AI/ML may still be useful for emulating computationally expensive physics models [Boe22]. AI/ML methods may also be useful for defining uncertainties in the nuclear data, through cross-reaction and cross-isotope covariances. As these data are used in applications to identify data sensitivities, and therefore drive new nuclear data needs, robust and defensible methods are needed.

Recommendation: A new, dedicated, cooperative 2.0 FTE effort should be established amongst multiple USNDP centers and external collaborators to design, build, test, and integrate AI/ML tools into the nuclear data pipeline for advanced compilation, evaluation, and dissemination. Recruitment and training of these individuals would likely start with post-doctoral researchers and take place over a 3-year time period.

Impact: Integration of AI/ML tools into the nuclear data pipeline reduces the time and cost associated with manual compilation of data and enhances the speed and accuracy of the evaluation process. In addition, this effort provides a connection to data scientists beyond nuclear science and modern data analytical techniques.

2.14 Create an Infrastructure for Data Preservation and Open Data

Issue: Within the US low-energy experimental nuclear physics community, there exists no centralized, comprehensive, searchable database of experimental data sets. The data are scattered (both in physical location and storage media type), not well documented, and typically not accessible over a network. Raw data are usually held by the original researcher and the associated analysis tools (methods, analysis codes, calibration data, *etc*.) are often lost. This results in a situation where data discovery, reuse, and reproducibility are often difficult or impossible.

Background: The ever-accelerating development of nuclear physics facilities and radiation detector systems, as well as the growing size of collaborations, results in a huge amount of nuclear data produced annually. For example, FRIB, the new world-class radioactive ion beam facility in the US for the study of nuclear structure, reactions, and astrophysics, will eventually explore more than 3,000 different isotopes with an expected data rate of petabytes/year. It is essential to appropriately preserve and effectively make use of these data.

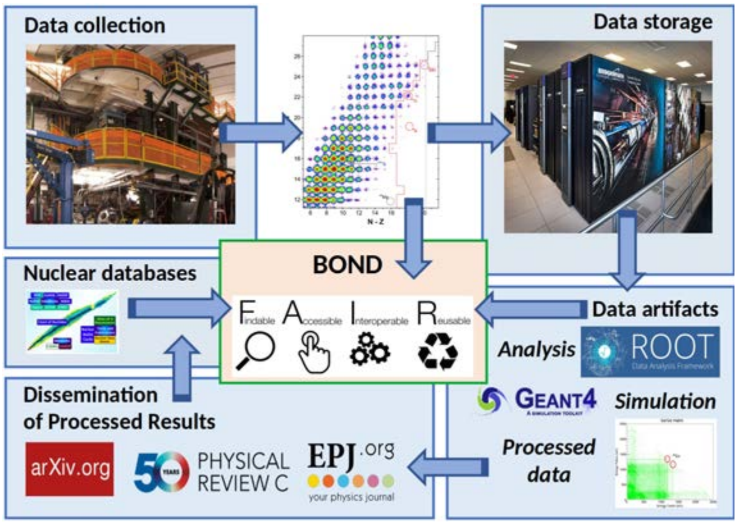

Figure 2.6: Flow of data from experiment to publication, storage, and dissemination

The field currently operates using "self-curation" of data by individual research groups, where the raw data and all associated analysis codes, simulations, and calibrations reside with the PI and perhaps a few collaborators. A subset of the processed data are published in a journal and only the data from the manuscript eventually gets compiled and evaluated in the USNDP databases. There are many disadvantages to this method of data preservation. Sophisticated data sets are seldom fully mined for all their richness, and often are only analyzed with a goal focused on a single issue and outcome, then shelved. This can result in repeating a costly experiment when data are, in fact, present but not publicly available. The lack of access to unpublished data from previous experiments hinders the ability of the community to best plan and design the next generation of experiments.

A better model for data preservation is indicated in Figure 2.6, where a FAIR (Findable, Accessible, Interoperable and Reusable) public storage facility, in which data are stored and eventually made accessible to the entire nuclear physics community, lies at the center. Such a facility would follow and connect each step of the scientific activities, beginning with data collection, through storage and analysis, finally ending with publication, dissemination to, and compilation in the nuclear databases. The recent memorandum issued by the Office of Science and Technology Policy (OSTP)[9] requests that publications and their supporting data resulting from federally funded research be made publicly accessible at the time of their publication [Nel22]. Our recommended FAIR data facility would fulfill the requirements laid out by the OSTP.

The sharing and analysis of data by many teams of scientists worldwide has now become routine in many fields. There are numerous examples of successful Open Data efforts from which the nuclear physics community can leverage efforts and customize tools. The Human Genome Project, a 13-year collaborative effort of 2,800 scientists [Lan01], was an Open Data pioneer, as were the NASA Open Data Project, offering access to more than 40,000 data sets[10]; the Sloan Digital Sky Survey, providing images and spectra from more than 3 million astronomical objects [Ahu20]; and the CERN ATLAS and CMS Open Data Project[11][Mal20]. The European nuclear physics community has recently taken the first steps toward Open Data in low-energy nuclear physics with the OpenNP initiative. With initial funding through EURO-LABS, this three-year project is aimed at developing a central service to provide access to all existing data sets and their associated software [Mat22].

Data preservation can be achieved with a centralized FAIR[12] [Wil16] Open Data/metadata repository for nuclear science data, actively curated by experts in the field. A single, consistent metadata schema can be used to provide persistent access using Persistent Identifiers (PIDs, *e.g.* Digital Object Identifiers (DOIs)) linking to experimental data, codes, principal results, non-numerical results such as level schemes, energy spectra, *etc*. Oversight by experts in nuclear science is essential to ensure FAIRness of the data, in particular completeness of the analysis methods, such as codes and calibration data, and reusability. Development of metadata should be guided by FAIR data principles with its emphasis on rich metadata at every stage of the data lifecycle, from raw data to analysis results. The key elements of an Open Data methodology would include the following:

- a FAIR Open Data repository for raw nuclear physics data;
- preservation of analysis methods, sort codes, auxiliary files, workflows;
- a metadata format carefully designed for nuclear research data (e.g., JSON and object-oriented metadata);
- an extensive metadata catalog allowing advanced search criteria;
- managed and backed-up physical servers for storing and accessing metadata and data;
- a containerized open-source server application to minimize the labor needed for expansion (e.g., using downloadable virtual machines[13] and docker "container" image[14]);

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[9] https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-Access-Memo.pdf
[10] https://data.nasa.gov
[11] https://opendata.cern.ch/docs/about
[12] https://www.go-fair.org/fair-principles/
[13] http://opendata.cern.ch/docs/cms-getting-started-2011
[14] https://opendata.cern.ch/docs/cms-guide-docker

- an open-source API to allow for search and discovery, and access for ML applications;
- hosting data on-site or linking to off-site storage;
- persistent identifiers to data and metadata (e.g., DOIs);
- a recommended Data Management Plan for researchers and funding agencies that takes advantage of the repository;
- tutorials, training, and yearly workshops to solicit feedback.

To ensure the smooth operation of a data repository and meet the requirements of its user communities, as well as maximize reuse of its data, one needs to define, implement and maintain clearly articulated policies and processes. These need to be agreed upon with user communities, sponsors, and other stakeholders to guarantee that they are workable, meet requirements, and integrate well with other related services. The definition of clearly articulated policies for data incorporation, sharing, embargo, and license for reuse are essential to adhering to FAIR data principles, and require cooperation between data preservation scientists and users. The involvement of the research community during development is crucial because the metadata and data content need to be beneficial to all research areas targeted by the centralized repository.

Recommendation: New support at the level of 2.0 FTE for 3 years followed by a decrease to a sustained 1.0 FTE level should be provided to develop a data and metadata architecture and management plan to enable the curation, preservation, and dissemination of low-energy nuclear physics data. Additional resources would also be required at approximately the $1M level for equipment to enable the data handling infrastructure. Some additional computer hardware funding will be needed as well. A coordinated education and outreach plan to the community of nuclear scientists should also be developed to encourage participation by the broader nuclear science and engineering community. Recruitment and training would likely start with post-doctoral researchers and take place over a 3-year time period.

Impact: The establishment of a world-class FAIR Open Data repository, for low-energy nuclear data will directly support data management requirements of DOE and other funding agencies, and the research that is subject to those requirements, to the benefit of the entire research community. It will help fully realize discovery potential of major facilities and universities, maximize return on investment, and extract additional physics using advanced analysis codes. An open data repository will serve as an excellent training ground for students and early-researchers and increase diversity by allowing everyone access to the data.

Furthermore, a centralized repository of data will allow the community to explore additional reaction channels, perform renormalization as “standards” change, and re-examine and validate published results. As the use of AI/ML increases, open data can also become a critical source of experimental data to train the defined algorithms.

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3 Diverse, Equitable and Inclusive Workforce Development

Nuclear data evaluation requires subject matter expertise in nuclear science and engineering, an understanding of the needs of a multitude of application end users, an understanding of the different parts of the nuclear data pipeline, and specialized training in the rules and practice of the evaluation process. While a Ph.D.-level scientist can provide subject matter and application training, knowledge of the nuclear data evaluation process requires specialized training alongside an established mentor. Furthermore, as the use of nuclear technologies expands from its historic roots in energy and national security into areas such as nonproliferation, targeted nuclear medicine, and space exploration, the evaluation workforce needs an expanded skill set to ensure they continue to meet the needs of society. To this end, in section 3.1, two recommendations are made for training a workforce capable of meeting modern nuclear data needs.

Retaining skilled evaluators is also key given the large investment in time and resources involved in their training. Members of the NSAC-ND subcommittee reached out to the domestic nuclear structure evaluation community to obtain recommendations for how to assist workforce recruitment and retention. Section 3.2 includes a distillation of the input obtained from the USNDP evaluation community.

3.1 Recruitment and Training

While the primary focus of this section is on the recruitment and retention of a nuclear data workforce starting with post-graduate education, the best approach is to begin recruitment from both 2- and 4-year colleges. Furthermore, targeting minority-serving institutions can access a new source of talent that has been largely untapped by the nuclear physics community. The research traineeships to broaden and diversify nuclear physics initiative[15], started in FY21, is a particularly valuable means of encouraging college students to consider graduate studies in nuclear science and engineering. Recent efforts at both the NNDC[16] and LBNL[17] are bearing fruit with students engaged in a variety of studies ranging from gamma ray spectroscopy and machine learning applied to neutron resonances at the NNDC to the development of an activation database for electronics testing for space effects at LBNL. ***Funding for these efforts should continue and members of the USNDP be encouraged to participate in similar programs, including the recently announced FAIR program[18].***

In addition to DOE-NP, several programmatic sponsors, including several components of the National Nuclear Security Administration, the DOE Office of Nuclear Energy, the Defense Threat Reduction Agency and the Nuclear Regulatory Commission recognize the importance of nuclear science and engineering expertise to their missions and are providing support through a host of graduate trainee and fellowship programs. However, most graduate students receive little to no

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[15] https://science.osti.gov/grants/FOAs/FOAs/2021/DE-FOA-0002456

[16] https://www.bnl.gov/newsroom/news.php?a=218986

[17] https://great-ns.lbl.gov/

[18] https://science.osti.gov/Initiatives/FAIR/-/media/grants/pdf/foas/2023/SC_FOA_0002931.pdf

exposure to the production of nuclear data. ***Support should be provided to USNDP members to aid in the development and execution of university-based and other training programs to raise awareness of nuclear data evaluation as a career option for graduate students.***

3.2 Retention

Virtually all nuclear data evaluators start their careers in a different area of nuclear science and engineering, with many becoming evaluators well after completion of one or more postdoctoral research appointments. Their training can then take upwards of 5 years working under the mentorship of an experienced evaluator. Given the typical burdened cost for training graduate students and postdocs ($50k-$100k/year) and national laboratory staff ($300k-$400k/year), each evaluator represents an investment well in excess of $2M, without considering the added costs associated with the peer-review of their early work products. ***The USNDP should create a robust evaluator retention plan.*** This plan should address the multi-faceted issues causing departures from the field and have buy-in from staff and commitment from management.

The lack of a well-defined career path can be discouraging to early-career researchers. As the nuclear data community grows and broadens in scope, thought should be given to a mechanism that provides opportunity for continued development in depth and breadth of knowledge. A retention plan designed by consultants with extensive experience in the complex, multi-faceted issues leading to departures should be adopted by USNDP leaders and well communicated and transparent to staff. This plan should reflect the changing needs of the members of the workforce as they progress through their careers, placing a high priority on professional development, onboarding and mentoring for early-career staff, and moving towards greater respect and recognition with a path to advancement for mid- to late-career evaluators.

A poll of the DOE-NP supported evaluators was conducted by the committee to help provide guidance for how to best retain evaluators. This poll led to the identification of several broad areas that are key to training and retaining a nuclear data evaluation workforce:

1. Development of a healthy workplace culture via the adoption of a code of conduct: A strong, inclusive culture communicates the mission, emphasizes teamwork, encourages creativity, fosters mutual respect, values diversity, challenges workers, and seeks to prevent burnout. The USNDP should work collaboratively to establish and enforce a code of conduct that reinforces a set of shared core values.
2. Polling and Feedback: Evaluators need a forum where they can provide open and anonymous feedback to database managers and editorial staff. Specifically, it was recommended that regular surveys should be conducted to identify issues and track them through to resolution and an anonymous online suggestion box should be implemented.
3. Training and development: Funded coaching/mentoring/shadowing programs should be provided to train evaluators in new topical areas (e.g., space exploration, isotopes, national security) and new approaches (e.g., machine learning, new data formats, open data) should be established. This could also be accomplished through the TNDC mechanism described above.

4. Recognition: A network-wide, decentralized recognition and reward program should be established that recognizes the talents and achievements of nuclear data community members.
5. Good Management Practices: Many staff departures can be caused by difficulties with management, so implementing good management practices is essential to boost retention. This is especially important in scientific fields where management and leadership training is not valued as highly as technical matters. Leadership training is necessary for those holding supervisory/editorial positions in the network that includes feedback from evaluators

3.3 Summary

The recruitment and retention of a diverse, equitable, and inclusive nuclear data workforce is required to address nuclear data needs. Crosscutting nuclear data efforts described in section 2.5 (statistical nuclear structure), 2.6 (fission), 2.9 (stopping powers) and 2.10 (high-energy reactions) of this report may require the creation of new training opportunities either domestically or in collaboration with international partners, such as the ICTP workshops described in section 3.1.1 of the first NSAC-ND report.

The USNDP should also create a robust retention plan, developed in a transparent manner, with both staff and management commitment. The plan should include multiple activities to deal with the many complex issues that drive departures and be relevant for younger, mid-career, and senior staff. The plan should also accommodate the policy requirements of the home institution of each member, the USNDP, the NNDC, and the DOE Nuclear Physics Office. Only by carefully crafting, implementing, and evolving such a retention plan can the USNDP ensure that it will have a diverse, inclusive, and talented workforce to sustain its important work long into the future.

4 Facility and Instrumentation Access Needs

Many of the nuclear data initiatives in section 2 require new measurements as well as evaluation. These measurements cover a wide range, with the vast majority involving neutron-induced reactions. This includes target fabrication capabilities as well as neutron, photon, stable and radioactive ion beams. These needs are summarized in Table 4.1 below.

Initiative Area	Sect.	Targets	Reactors	Neutron beams	Photon beams	Stable beams	Radioactive Ion Beams
Astrophysics	2.4	■		■	■	■	■
Statistical Data	2.5	■			■	■	■
Fission	2.6	■	■	■	■	■	■
Decay Data	2.7	■				■	■
(n,x) data	2.8		■	■			
Stopping Powers	2.9	■				■	
Fusion Energy	2.11	■	■	■			

Table 4.1: Facilities needed for nuclear data initiative measurements described in Section 2.

Experimental capabilities exist at both national laboratories and universities throughout the world with both unique and complementary capabilities to carry out this work. While some of these are "flagship" facilities supported by a major program, such as DOE-NP's Facility for Rare Isotope Beams (FRIB) and the NNSA's Los Alamos Neutron Science Center (LANSCE), others are based at smaller national laboratories and universities and offer unique capabilities that are particularly well-suited to determining neutron- and gamma-induced reaction data. Many of these smaller facilities also play a crucial role in recruiting and training nuclear scientists and engineers. They include the accelerator-based neutron and gamma-ray sources at Ohio University, Triangle University National Laboratory, the University of Massachusetts – Lowell, the University of Kentucky, Rensellaer Polytechnic Institute and the LBNL 88-Inch Cyclotron. Other accelerator facilities providing important training opportunities include Notre Dame University, Florida State University, and Texas A&M University ***It is crucial that these smaller facilities continue to be supported and integrated into any national nuclear data plan.***

Detailed descriptions of many of these facilities were assembled in Appendix D of the Nuclear Data Needs and Capabilities for Applications (NDNCA) Workshop Whitepaper produced in 2015 [Ber15][19]. A revised version of the NDNCA Appendix D containing updates for facilities at LBNL, Ohio University, Triangle University Nuclear Labs and the reactor at North Carolina State University is attached to this report as Appendix A. ***A periodic reassessment of these facilities should be performed by the USNDP to aid experimentalists in determining which facilities are best suited to address a particular nuclear data need***.

In this section a high-level overview of several of the facilities and the instrumentation needed to carry out these measurements is provided, organized by the type of beam produced. This overview will include a description of how access is allocated (e.g., by a competitive beam-time proposal submitted to a Program Advisory Committee, through collaboration with in-house staff, beamtime purchase through a recharge mechanism, etc.).

4.1 Target Fabrication

High-purity targets with well-defined thickness and purity are essential for most critical nuclear data measurements. This includes both stable, and increasingly, radioactive nuclides. The DOE Isotope Program maintains the capability to produce target materials and to form targets for DOE and other entities. Materials production capabilities include stable isotope enrichment and radioisotope production. Target materials and formed targets can be ordered through the National Isotope Development Center. These capabilities are described at greater length in Appendix A.1.

The DOE Isotope Program holds an annual meeting with a broad range of federal agencies to solicit new and ongoing isotope needs, including those for nuclear data experimental targets. It is important for the researcher to ensure that their target needs are expressed to the appropriate funding agency or to the Isotope Program.

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[19] https://bang.berkeley.edu/events/ndnca/whitepaper/

Experimental groups throughout the nuclear science community have developed in-house target fabrication capabilities for specific needs that are not regularly available. The fabrication of bespoke targets requires a blend of talents and equipment. ***A sustained training pipeline needs to be developed to train the next generation of target makers.***

4.2 Reactors

The design of advanced thermal reactors, identified in the first three rows of Tables 2 and 3 in section 4.2 of the first NSAC-ND report, requires the ability to accurately model neutron thermalization, which is in turn dependent on having well-characterized thermal scattering laws (TSLs) for the constituent materials. Computation is the primary tool used to obtain nominal values and covariances for TSLs, as described in section 4.2.4 of the first NSAC-ND report. However, experimental benchmarking using nuclear reactors is essential as well [NEA20]. Facilities such as the PULSTAR reactor at North Carolina State University[20] offer both the technical capability and in-house expertise required to improve TSL data through a combination of measurement and analysis/interpretation.

In addition to TSL benchmarks, integral measurements of capture and fission cross sections, and materials damage benchmarks are conducted at research reactors. The HFIR at ORNL, the Advanced Test Reactor (ATL) at INL, and university-based facilities including the McClellan reactor, maintained by UC Davis[21], and the Missouri University Research Reactor (see Appendix A.12)[22] offer complementary research capabilities for nuclear data measurements.

4.3 Neutron beam facilities

Neutron-induced reactions on stable or long-lived targets account for the vast majority of the nuclear data needs presented in the first NSAC-ND report, including Nuclear Energy (section 4.2) 4.2), National Security (section 4.4), Nonproliferation (section 4.5) and both Planetary Nuclear Spectroscopy and Defense (sections 4.6.4 and 4.6.6, respectively). Access to neutron beams is also key for the (n,x) data initiative described in section 2.8 of this report. While the majority of these nuclear data needs are for (n,x) reaction cross sections, other quantities, such as fission product and prompt gamma-yields are needed as well.

Neutron beam facilities also provide important data regarding off-yrast structure, with work from both *Demidov* [Dem04] and *Fotiades* [Fot10] showing the importance of these (n,x) data for eliminating spurious levels from ENSDF. (n,x) reactions on short-lived radioactive nuclides are also important for some topics in the Nuclear Astrophysics section of the first NSAC-ND report (section 4.1.2).

The production of neutron beams is technically challenging since neutrons are short-lived secondary reaction products that cannot be manipulated using external electric and magnetic fields.

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[20] https://nrp.ne.ncsu.edu/

[21] https://mnrc.ucdavis.edu/

[22] https://www.murr.missouri.edu/

There are a handful of light-ion induced reactions that can produce monoenergetic neutron beams with energies below 20 MeV. Neutron production using higher-energy proton beams and time-of-flight measurements are complementary production mechanisms.

The flagship NNSA neutron source is the Los Alamos Neutron Science Center (LANSCE). LANSCE[23] hosts two broad-energy neutron time-of-flight sources driven by an 800 MeV proton linac. A detailed description of LANSCE can be found in Appendix A.11. LANSCE has a wide array of instrumentation for measuring (n,x) data including the Chi-Nu array [Lee13, Hai12, Kel20] of neutron scintillators optimized for measuring ($n,n'g$), the LENZ array [Lee16, Kuv20] for measuring (n,px) and ($n,\alpha x$) reaction cross sections, the SPIDER array [Tov13] for (n,f) measurements of fission fragment energies, and the DANCE spectrometer [Mos14] for (n,g) measurements in the resonance region. Beam time is available via a competitive PAC-reviewed proposal process.

The combination of broad energy range, good timing structure and excellent instrumentation makes LANSCE a preeminent facility for neutron-induced reaction studies. However, multi-hundred MeV spallation neutron sources such as LANSCE are often less than ideal for measuring nuclear data involving incident neutron energies below 20 MeV due to difficulties in characterizing multiple scatter from the high-energy portion of the beam. Furthermore, multi-100 MeV neutrons preclude the use of activation as integral validation for (n,x) reactions involving neutrons with incident energies below 20 MeV. Fortunately, there are a host of university- and small-laboratory based facilities with neutron sources at a lower overall maximum energy. Many of these capabilities are described in Appendix A of this report including the Triangle University Nuclear Laboratory (TUNL), the Edwards Accelerator Laboratory at Ohio University, the University of Kentucky neutron source, the LINAC at RPI, and the thick target deuteron breakup neutron source [Har18] at the LBNL 88-Inch cyclotron. These measurements have dramatically lower uncertainties in neutron flux determination as compared to in-beam measurements made with high-energy white neutron sources such as LANSCE. While access to all the university facilities requires collaboration with a local researcher and/or an hourly cost for using the machine, these venues offer the opportunity to teach students and early career scientists about the importance of nuclear data.

The Gaerttner Laboratory at Rensellaer Polytechnic Institute (RPI) houses a capability intermediate between the university facilities described above and LANSCE. RPI couples a 9-60 MeV electron linac to a broad suite of neutron and gamma-ray spectrometers on several short and long neutron time-of-flight lines. The timing structure of the RPI facility (5-5000 ns width with a tunable repetition rate of 1-400 Hz) is particular well-suited to the resonance region, covering a unique niche in neutron spectroscopy needed for energy and national security applications. RPI is undergoing an upgrade to 150 MeV with 10 times higher intensity), More detail about the RPI facility can be found in section A.18 of the Appendix.

In addition to the spectrometers at LANSCE mentioned above, there are a number of unique instrumentation capabilities at the lower-energy neutron facilities. LBNL houses the Gamma

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[23] https://lansce.lanl.gov/

Energy Neutron Energy Spectrometer for Inelastic Scattering (GENESIS)[24] which can provide energy and angle differential neutron and gamma-ray cross sections. GENESIS directly supports the nuclear reaction evaluation efforts described in section 2.2 of this report since inelastic scattering cross sections play a critical role in modeling nuclear systems undergoing fission, and the current nuclear data assessments disagree on the balance between elastic and inelastic cross sections, necessitating modern differential measurements.

LBNL and TUNL also both have "Rabbit" systems that transfer samples rapidly from the neutron irradiation location to locations where decay radiation can be measured. These are the Fast Loading Unloading Facility for Fission Yields (FLUFFY)[25] at LBNL and the RApid Belt-driven Irradiated Target Transfer System (RABITTS)[26] at TUNL [Ton22]. Both perform the rapid transport ($\leq$0.7 s) of a capsule containing target samples between a neutron beam and an HPGe clover array. The rapidity of this transport allows measurement of short-lived fission product yields when an actinide sample is loaded in the capsule. These fission product yield and gamma-decay measurements support both the fission and accelerated decay data initiatives described in sections 2.6 and 2.7 of this report respectively.

Taken together, these high- and low-energy neutron sources provide a more complete "toolkit" for addressing differential (n,x) nuclear data needs.

Integral Benchmarks also provide important data for nuclear reaction evaluation. Los Alamos maintain several such capabilities at the National Criticality Experiments Research Center (NCERC) which is described in the Appendix A.13. Additional benchmark capabilities for higher (DT) neutrons are needed to address the needs listed in the Fusion initiative in this report as well as active interrogation for nonproliferation applications described in Section 4.5 of the first NSAC-ND report.

4.4 Gamma-ray facilities

Gamma-ray beams are a key tool for directly addressing nuclear data needs listed in the first report, such as photo-nuclear cross sections for isotope production (first report, section 4.3.4) and active interrogation for nonproliferation (first report, section 4.5.6.5) and even for the development of space-based nuclear reactors (first report, section 4.6.5). Gamma-ray sources also provide insight into the statistical nuclear structure (section 2.4) needed to improve nuclear reaction modeling for astrophysics (section 2.3) as well as fast reactor design (first report, section 4.2).

The flagship domestic gamma-ray beam facility is the High Intensity Gamma Source (HIgS) free electron laser light source at Duke University. A schematic layout of the facility is shown in the first figure in Section A.20 where HIgS is described.

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[24] https://nucleardata.berkeley.edu/projects/genesis.html
[25] https://nucleardata.berkeley.edu/projects/fluffy.html
[26] https://tunl.duke.edu/research/our-research/applied-nuclear

Other gamma-ray facilities offer broad-range and quasi-monoenergetic photon capabilities such as the BELLA facility at LBNL[27] and PRISM at LLNL.

4.5 Light and Heavy-Ion Stable Beams (*E/A*≤20 MeV•amu)

Light- and heavy-ion stable beam facilities provide valuable experimental capabilities that provide much of the data needed for nuclear structure (section 2.1), reaction (section 2.2), atomic masses (sections 2.3) and astrophysics (section 2.4) evaluation described. These facilities are also needed for light- and heavy-ion stopping power measurements described in section 2.9 of this report. They also support High Energy Accelerator Production of Isotopes (first report, section 4.3.2 and section 2.10), Ion Beam Therapy (first report, section 4.3.6) and Space Radiation Protection (first report, section 4.6.3).

Two light- and heavy-ion stable beam facilities are available at DOE-NP national laboratories to support nuclear data measurements: the Argonne Tandem and Linear Accelerator System (ATLAS) at Argonne National Laboratory and the 88-inch cyclotron at Lawrence Berkeley National Laboratory. Both of these facilities house USNDP centers, expediting the integration of measured data into the nuclear data evaluation process and serving the nuclear data thrust areas and initiatives described in sections 2.1, 2.3, 2.4, 2.5, 2.6 and 2.7. These facilities are described in greater detail in sections A.1 and A.7 of Appendix A respectively.

ATLAS is the premier domestic stable beam facility. The first figure in Section A.1 shows the ATLAS facility. Access to ATLAS is provided via submission to a Program Advisory Committee (PAC). ATLAS provide beams above the Coulomb barrier for all stable isotopes from protons through uranium, as well as beams of long-lived nuclides, including minor actinides beyond uranium. In addition, the RAISOR/AIRIS facility produces short-lived beams via the in-flight technique. In conjunction with the Californium Rare Ion Breeder Upgrade (CARIBU), which adds pure, neutron-rich fission products (FP) to the array of available ion beams, ATLAS provides a broad and unique suite of isotopes for various ND studies. In order to maximally benefit from this resource, the Physics Division at Argonne develops and maintains an inventory of state-of-the-art detector systems and support facilities that provide unique capabilities in multiple nuclear data areas that are not only critical for studies of nuclear astrophysics and fundamental nuclear structure, but also for national security and nuclear energy missions, including but not limited to, nuclear forensics and safeguards, nuclear energy and associated fuel cycle operations, materials analysis, medical diagnosis and radiotherapy, and passive and active interrogation applications.

In addition to the intense thick-target deuteron breakup neutron beam capability described in section 4.2, the 88-inch cyclotron at LBNL [Kir18] provides a wide range of intense charged particle beams from hydrogen through uranium with energies up to 20 MeV/amu. These beams have been used to perform a wide range of light-ion charged particle measurements for isotope production [Mor20, Fox21a, Fox21b] in support of high-energy charged-particle cross section measurements described in section 2.9 and section 4.3 in the first NSAC-ND report, activation

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[27] https://bella.lbl.gov/

standards measurements [Ble22, Ble21] to aid in nuclear reaction evaluation (section 2.2), and materials damage studies [Ste22] in support of the fusion energy initiative described in section 2.10.

The 88-inch cyclotron also houses the Berkeley Accelerator Space Effects (BASE) facility that uses "cocktail" beams of heavy ions with similar cyclotron frequencies to uniformly dose electronics for single event effects (SEE) electronics damage testing. These beams provide a unique possibility to address deficiencies in charged particle stopping powers for detector design, ion beam therapy and space exploration described in section 2.8 via time-of-flight measurements [Amm11]. Beam time for these experiments, including development time for the time-of-flight set-up, could be supported either by DOE-NP or by the BASE partner organizations. Similar capabilities also exist or are under development at Texas A&M university as well.

4.6 High Energy Beams ($20 < E/A$ (MeV/amu) < 50)

As mentioned in section 2.7, most reaction evaluations have been focused on neutron-induced reactions with incident energies below 20 MeV. However, the production of radioisotopes for medical applications (first report, section 4.3.2) and the use of ion beam therapy (first report, section 4.3.6) for the treatment of disease both require nuclear reaction data up to several hundred MeV. Space and aerospace applications require nuclear reaction data to much higher energies ($E/A \leq 10$ GeV) to model damage in electronics and dose to astronauts (first report, section 4.6.3). These needs led to making the measurement and modeling of nuclear reaction up to 10 GeV/amu, described in section 2.9, a new thrust area in this report.

Three domestic facilities exist that provide proton beams at 100-500 MeV/amu: the Isotope Production Facility at Los Alamos National Laboratory (LANL-IPF)[28] and the Brookhaven Linac Isotope Producer (BLIP)[29] and NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory[30]. LANL-IPF and BNL-BLIP are described in sections 7.8 and 7.4 of Appendix A.

The NASA Space Radiation Laboratory at Brookhaven National Lab, has been constructed and extensive measurements have been made for ions with energies below 3 GeV/n. However, no data exist for energies above 3-50 GeV/n. The Space Radiation Protection community has identified this high energy regime as an area of national need. Currently, there are only two facilities in the world which can produce ion beams in this energy range: RHIC at BNL and the SPS at CERN. The STAR detector at RHIC has the excellent light fragment capabilities needed for these measurements. RHIC can deliver the ions and energies needed by the Space Radiation Community. STAR and the Collider Accelerator Division at BNL, having developed the fixed-target program at RHIC, are leading the effort to make these cross section measurements. A target mount to hold carbon (simulated astronaut), aluminum (simulated space craft), and nickel

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[28] https://lansce.lanl.gov/facilities/ipf/index.php
[29] https://www.bnl.gov/mirp/blip.php
[30] https://www.bnl.gov/nsrl/

(simulated equipment) targets inside the beam pipe at the STAR experiment. These targets were installed in fiscal year 23 and a proposal has been developed to determine the necessary beam time at RHIC to irradiate these targets with high energy carbon, aluminum, and iron beams to simulate high energy galactic cosmic rays. Each beam would be run at three energies, 5, 20, and 50 GeV/n, and would irradiate each of the three targets for six hours. The total time needed for machine setup, beam development, and target irradiation would be two weeks. The measurements would be differential cross sections ($d^2\sigma/dEd\Omega$) for angles from zero to ninety degrees for p, d, t, ^{3}He, and ^{4}He. One degree angular steps would be taken from zero to seven degrees, which is covered with the STAR forward tracker and calorimeters, and ten degree angular steps would be taken from 10°-90°, which is covered by the time projection chambers and time-of-flight systems. This effort is being championed by Prof. Daniel Cebra from UC-Davis.

4.7 Radioactive Ion Beams

The Facility for Rare Isotope Beams (FRIB)[31] is the leading low-energy nuclear physics user facility for the U.S. Department of Energy Office of Science (DOE-SC). FRIB will produce a new body of nuclear data relevant to the core of curiosity-driven nuclear science including structure (section 2.1), reaction (section 2.2) and mass (section 2.3) evaluation. FRIB will also provide critical information for several of the proposed nuclear data initiatives including nuclear astrophysics (section 2.4) and statistical nuclear structure (section 2.5) and fission theory (section 2.6). FRIB also offers a venue to address some high-priority decay data (section 2.7), although much of this area could likely be addressed using the stable beam facilities described in section 4.4 above.

FRIB is based on a 400 kW driver linear accelerator (linac) providing world-leading rare-isotope beam intensities. FRIB is open to researchers from around the world based on the merit of their proposals for scientific research consistent with DOE-SC policy and U.S. law. Beam time is granted by the FRIB Laboratory Director based on recommendations from a Program Advisory Committee (PAC). There is no charge for beam time under the condition that researchers publish their results, making them available to the scientific community. At FRIB, primary stable ion beams provided by the linac are incident upon a rare-isotope production target that produces a cocktail of reaction products from projectile fragmentation reactions. The reaction products of interest are isolated in-flight using a fragment separator and then delivered to experimenters in three general energy regimes. The fragmented beams may be used in-flight at energies as high as a few 100 MeV/u. Those beams can be thermalized in a gas catcher and delivered to low energy experimental areas at energies below 60 keV/u. The thermalized beams can also be reaccelerated and delivered to the ReA3 and ReA6 experimental area at energies between 0.3 and 12 MeV/u. A large number of state of the art detector systems are available at FRIB, either as lab-supported devices or in collaboration with the local group.

Other domestic radioactive ion beams facility exist as well at Texas A&M and ANL and are described in the Appendices.

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[31] https://frib.msu.edu

5 Conclusions and Acknowledgements

In the last five years, the use of nuclear technologies to address some of the most compelling societal needs has blossomed into new efforts. New cancer treatment using targeted alpha therapy [Bai20, Pou21], the generation of carbon-free energy using next generation fission reactors,[32] achieving thermonuclear ignition at the National Ignition Facility,[33] exploration of the moon[34] and the outer solar system,[35] ensuring the safety and reliability of the nation's nuclear deterrent,[36] and limiting the illicit spread of nuclear weapons [Rom18], all require quality nuclear data. Addressing these needs requires a significantly expanded US Nuclear Data Program that can provide service well outside of its traditional role supporting the basic nuclear science community. Based on the nuclear data needs provided in the first NSAC-ND report, 11 new nuclear data initiatives have been presented, along with a recommendation for continued support for the three existing core nuclear data activities. Key to all of these is a comprehensive plan to recruit and retain a diverse, equitable and inclusive workforce, that will allow the USNDP to support the nation in its quest to fully realize the benefit of these new technologies.

The central importance of nuclear data to both basic and applied science will necessitate that the USNDP transform from the "quiet librarian" of nuclear structure data to a partner in efforts to face the most compelling challenges of the 21st century. It will also demand significant coordination between numerous government agencies, international nuclear data organizations and the private sector. While this is an ambitious charge, the rewards for success would be equally dramatic, enabling the nation to address existential threats from climate change to national security, nuclear proliferation, dependence on foreign energy sources, exploration of the solar system, development of novel treatments for human disease, and beyond.

In closing, the chair would like to acknowledge the efforts of the entire subcommittee and give special thanks to Michael Smith and Caroline Nesaraja for their work polling USNDP nuclear structure evaluators regarding workforce retention and to Bethany Goldblum for developing the format for the nuclear data initiatives in section 2 and for her contributions to the AI/ML section. I would also like to thank my colleagues in the USNDP who provided significant input to the nuclear data initiatives in section 2, including Dave Brown, Gustavo Nobre, Libby McCutchan and Jin Wu from the NNDC (sections 2.1, 2,2, 2.11 and 2.13), Michael Smith and Caroline Nesaraja (section 2.1, section 2.3 and 2.12) and Aaron Hurst (section 2.8). Special thanks are due to Drs. Gail Dodge, Catherine Romano, Ramona Vogt, Bethany Goldblum and Jo Ressler for reading through the entire document both as copy editors and contributors on multiple occasions. Their contributions were essential to the production of this document.

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[32] https://www.terrapower.com/natrium-demo-kemmerer-wyoming/

[33] https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/

[34] https://www.nature.com/articles/d41586-022-02293-8

[35] https://civspace.jhuapl.edu/destinations/instruments/dragns

[36] https://www.energy.gov/nnsa/articles/stockpile-stewardship-and-management-plan-ssmp

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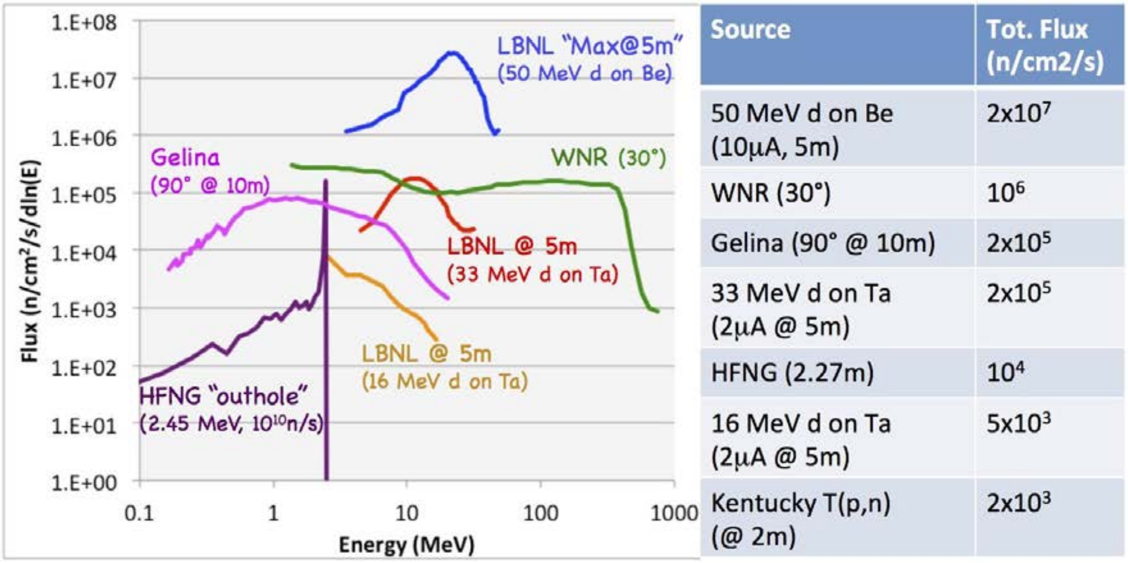
7 Appendix A: Nuclear Data Facilities

The need to generate nuclear data for applications can arise from either a lack of key information, or from a situation where discrepant experimental data limit confidence in evaluation. In some cases, only modest precision is required for improvement, while in others increasingly precise data provides greater benefit for the application. In some situations, modest improvements in the quality of available nuclear data can be gained using straightforward and simple experimental approaches; while in others, improvements can only be obtained by significant rethinking of experimental techniques. One concept that became clear in the workshop was that no one facility was capable of addressing the entire spectrum of nuclear applications.

Fortunately, the capabilities and facilities available in the United States for applied nuclear science are robust diverse. In some cases, such as the Gaerttner LINAC Center at RPI, the detector and beam characteristics are focused on the production of data relevant for nuclear energy. Others, such as the Weapons Neutron Research (WNR) facility at LANL and the National Ignition Facility (NIF) at LLNL, emphasize national security needs such as stockpile stewardship and counter-proliferation. In contrast, facilities like ANL and NSCL have broad reaching capabilities that can potentially contribute to either curiosity- or application-driven projects.

That being said, while the primary focus of curiosity-driven low-energy nuclear science involves studying nuclei far from the valley of stability, the needs of the applications communities presented in this workshop tended to focus more on neutron-induced reactions on stable nuclei, with the notable exceptions being charged particle reactions for medical isotope production. Since neutron beam are amongst the first radioactive beams, most of the neutron facilities discussed in the workshop utilized "secondary beams" formed from either charged-particle induced nuclear reaction products (LANL, RPI, TUNL, Ohio, Kentucky RPI, LBNL *etc*.) or from fission at reactors, such as MURR and HFIR at ORNL. The US is fortunate to host such a wide range of neutron beam facilities.

One of the challenges facing a researcher interested in performing neutron reaction studies is to choose which facility provides the optimal blend of neutron beam characteristics (pulse structure, flux, energy range) and detector capabilities to obtain the required data. Darren Bleuel (LLNL) attempted to help in this decision making process by producing a comparison of neutron capabilities at different pulsed beam facilities as a part of the NDNCA whitepaper [Ber15]. Figure 6 below shows the flux and energy spectrum of a number of neutron sources available to the applications community. These include the thick-target deuteron breakup neutron source at LBNL, the Weapons Nuclear Research (WNR) facility at LANL (green curve), and the Gelina neutron source in Brussels. A "typical" monoenergetic CW neutron source, the UC Berkeley quasi-monoenergetic High-Flux Neutron Generator (HFNG) is presented for comparison purposes. It should be noted that the comparison by Dr. Bleuel was by no means comprehensive, in that it excluded a number of other important neutron sources, such as the (α,n) neutron source at RPI. Fortunately, these facilities are well described in their own sections of this appendix.



Source	Tot. Flux (n/cm2/s)
50 MeV d on Be (10μA, 5m)	2x10^7
WNR (30°)	10^6
Gelina (90° @ 10m)	2x10^5
33 MeV d on Ta (2μA @ 5m)	2x10^5
HFNG (2.27m)	10^4
16 MeV d on Ta (2μA @ 5m)	5x10^3
Kentucky T(p,n) (@ 2m)	2x10^3

Figure 6. Comparison of the neutron flux available at several neutron facilities (from the talk by Bleuel).

Many of the neutron facilities described in this work utilize light charged particles (*p*, d, t, ^{3}He, or *a*). This is a "happy coincidence" in that the much of the nuclear data needs relevant to medical isotope production center on light-ion production cross section measurements. This potentially allows a number of facilities described in this whitepaper to serve the needs of all three major applications topics (Nuclear Energy, National Security, and Isotope Production). Examples of facilities in this category include the 88-Inch cyclotron at LBNL, the tandem accelerator at TUNL and the Edwards Accelerator Lab at Ohio University.

A "third class" of facility discussed here is the High Intensity Gamma Source (HIGS), which produces monoenergetic photon beams through the use of a free electron laser: This provides a unique capability for measuring (g,g') and (g,*n*) cross sections. These cross sections are needed for a number of national security applications.

Along with issues such as beam and detection capabilities and sensitivities, the issues of beam-time allocation and detector/spectrometer availability are non-negligible. While some facilities operate as user facilities with rather straightforward opportunities for collaboration in connection with beam availability, others operate utilizing highly competitive Program Advisory Committees that review the scientific merit of any proposed experimental work, and others may use a cost-center model, in which beam-time charges of tens to hundreds of thousands of dollars per week are typical.

The goal of this Appendix is to provide a review of the capabilities at many of the facilities available for applied nuclear science research in the US that can be used by experimentalists who are planning to carry out applications-relevant nuclear data measurements. This list has been kept as broad as possible. Although it is undoubtedly incomplete, every effort was made to have it be representative of the broad spectrum of facilities at hand. Lastly, it should be noted that most of the text in the individual facility descriptions was provided by the points-of-contact (POC) at each institution, and that only minor revision of the content has been made. Users of this Appendix are encouraged to contact the listed facility POC for additional information.

7.1 A.1: Argonne National Laboratory, Atlas/CARIBU Facility

General Description: US DOE low-energy nuclear physics national user facility. Provides stable and radioactive beams at low and Coulomb barrier energy.

Accelerator: ATLAS heavy-ion superconducting linac

Beams:
- All stable beams from proton to uranium at high intensity and energies up to 20 MeV/u for the lightest beams and 10 MeV/u for the heaviest
- Over 500 mass separated beams of neutron-rich isotopes produced by ^{252}Cf fission, available at low energy or reaccelerated to 2-15 MeV/u
- In-flight produced light radioactive beams one or two neutrons away from stability at energies of 5-20 MeV/u

Beam time is allocated by PAC.

Research Focus (relevant to applications): measurement of properties (mass, beta-delayed neutrons/gammas) of fission fragments, accelerator mass spectrometry of heavy elements, single particle structure, surrogate reactions

Present detector array capabilities (relevant to applications): Canadian Penning trap mass spectrometer, beta-delayed neutron trap, X-array and tape station, Gammasphere, HELIOS, MANTRA AMS system

Contact person: Guy Savard

The Argonne Tandem Linac Accelerator System (ATLAS), developed and operated by Argonne National Laboratory's (ANL) PHY Division as a national user research facility for the Department of Energy, Office of Science, Nuclear Physics, is a world-class superconducting accelerator complex. It can provide beams above the Coulomb barrier for all stable isotopes from protons through uranium, as well as beams of long-lived nuclides, including minor actinides beyond uranium. In addition, the RAISOR/AIRIS facility allows for the production of short-lived beams via the in-flight technique. In conjunction with the Californium Rare Ion Breeder Upgrade (CARIBU), which adds pure, neutron-rich fission products (FP) to the array of available ion beams, ATLAS provides a broad and unique suite of isotopes for various ND studies. In order to maximally benefit from this resource, PHY develops and maintains an inventory of state-of-the-art detector systems and support facilities that provide unique capabilities in multiple ND areas that are critical to studies of not only nuclear astrophysics and fundamental nuclear structure, but also to national security and nuclear energy missions, including but not limited to, nuclear forensics and safeguards, nuclear energy and associated fuel cycle operations, materials analysis, medical diagnosis and radiotherapy, and passive and active interrogation applications.

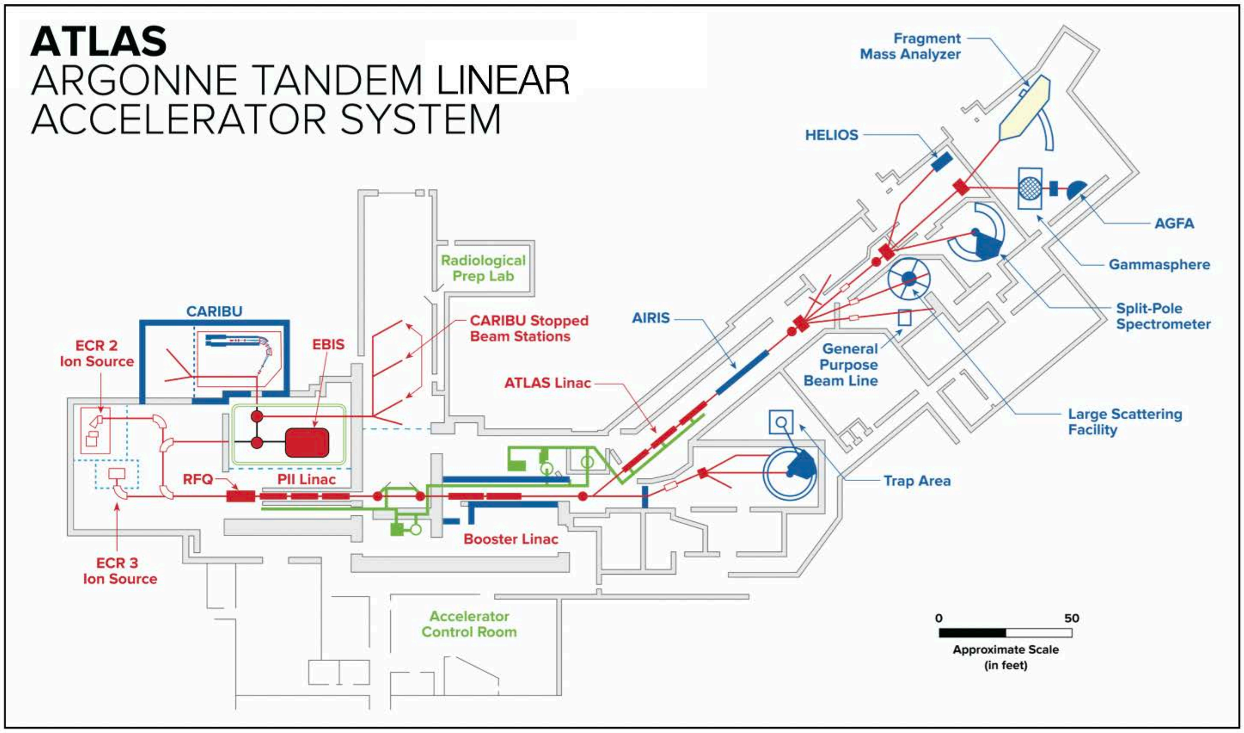


Figure 1: Layout of the ATLAS facility

Neutron-induced capture and fission cross-sections: In addition to ATLAS's already demonstrated capabilities in Accelerator Mass Spectrometry (AMS), the HELIOS solenoidal spectrometer is a unique instrument that can provide both improved precision on existing cross-section data as well as unique ND for neutron-induced capture and fission reactions on long-lived actinide isotopes. Additionally, a planned upgrade of CARIBU will allow for indirect (surrogate) measurements of neutron-induced capture cross-sections previously inaccessible to the research community on short-lived isotopes in the FP region.

Measurements of prompt and delayed gamma-rays and neutrons from fission: PHY has the capability to conduct precise measurements of prompt and delayed gamma-rays and neutrons for all FP. Using the Gammasphere spectrometer such fission signatures can be measured with unprecedented energy resolution and resolving power. In addition, prompt and delayed neutrons can also be measured by means of the neutron-shell detector array. Capabilities exist for dedicated beta-delayed neutron measurements as well.

Figure 2: CARIBU facility at ATLAS

Fission product yields (FPY): PHY maintains and operates a dedicated Penning Trap spectrometer that can be used to directly measure the independent and commutative fission product yields with a part per million resolution for all FP. The CARIBU upgrade will enable further neutron-induced direct FPY measurements with unprecedented accuracy to be carried out for a number of fissile nuclides and it would also allow energy-dependence of neutron-induced FPY to be studied. In addition, PHY also operates the X-Array and SATURN moving-tape detector system, which can be used to measure FPY of short-lived radionuclides by means of beta and gamma detection.

Below are more technical details on the detectors and facilities at PHY involved in ND research, as well as planned upgrades and additional capabilities:

Figure 3: State-of-the-art detector systems developed, maintained, and operated by PHY: HELIOS (top left), X-array/SATURN (top right), Gammasphere (bottom left), CPT (bottom right).

- Gammasphere is one of the world's most powerful spectrometers for γ-ray coincidence data research. It consists of up to 110 high-purity, Compton-suppressed germanium detectors in a spherical arrangement, allowing for both discrete γ-ray spectroscopy and calorimetric total absorption spectroscopic approaches to be carried out simultaneously. Additionally, up to 35 forward modules on Gammasphere can be replaced with liquid-scintillator Neutron Shell modules for neutron detection.
- X-array is a highly-efficient array of high-purity germanium clover detectors for γ-ray detection, and SATURN (Scintillator And Tape Using Radioactive Nuclei) is a plastic scintillator detector

combined with a tape-transport system for detection of beta particles and removal of long-lived isobaric decay activities produced in the decay of FP. When coupled together, the decay properties of neutron-rich isotopes from CARIBU such as half-lives and branching ratios can be measured with high precision.

- The Canadian Penning Trap (CPT) is used to conduct precise mass measurements on products from CARIBU by using their precession frequency. Due to its incredible mass resolving power, it can even separate isomers and measure their fission yield branches down to the 10^{-6} level.
- HELIOS (Helical Orbit Spectrometer) is a charged-particle spectrometer designed for the study of nuclear reactions in inverse kinematics. Inverse kinematic reactions are a necessity for studying ND with radioactive beams, but measurements of these reactions often result in poor resolution when using conventional detector techniques. HELIOS's solenoidal design, pioneered by PHY, overcomes these difficulties to provide high-resolution measurements that can be used to study (n, γ) and (n, f) reactions that were previously difficult or impossible to probe precisely.

Beyond these current capabilities, PHY plans two substantial upgrades of the ATLAS facility that will expand its ND capabilities: the neutron generator upgrade to CARIBU (nuCARIBU), which will add neutron-induced fission products from any actinide target to the already incredible range of ion beams ATLAS can deliver, and the multi-user upgrade (MUU), which will allow for simultaneous use of both stable and radioactive accelerated ion beams through ATLAS in order to substantially increase available beam time at the facility.

Critical to all its current and potential ND research, PHY has extensive expertise and capabilities in performing nuclear data evaluations for the broader science and applied community. Additionally, PHY has advanced Monte Carlo computing and simulation capabilities, as well as access to ANL's supercomputing facilities. A condensed summary of how PHY's capabilities impact various ND topics is shown in the table below.

ND Type	PHY Capabilities	Advantages of PHY Capabilities
(n,γ), (n,f) cross-sections	HELIOS, ATLAS, CARIBU, nuCARIBU, CATS, TRACER	Surrogate measurements of (n,γ) and (n,f) cross-sections on all long-lived actinides; (n,γ) cross-sections on short-lived FP; AMS
Measurements of prompt and delayed fission gamma rays and neutrons	Gammasphere, Neutron Shell, ATLAS, CATS	High-resolution gamma-ray data not achievable via standard techniques; neutron detection capabilities
FPY data	CARIBU, nuCARIBU, CPT, X-array	Direct, high-resolution FPY measurements on all FP in both ground and isomeric states; isomeric separation down to 10^{-6}; complementary activation FPY measurements on short-lived FP and isomers
FP and actinide decay data (branching, half-lives, etc.)	CARIBU, nuCARIBU, X-array, SATURN, Gammasphere	High-precision measurements using state-of-the-art instrumentation combined with extensive expertise and experience in ND evaluation

7.2 A.2: Brookhaven Linac Isotope Producer (BLIP)

U.S. DEPARTMENT OF
ENERGY
Office of Science

Isotopes
For Science, Industry, and Medicine
U.S. Department of Energy

General Description: Radionuclide Production for DOE Isotope Program is part of the Collider-Accelerator Department at Brookhaven National Laboratory; not a user facility but maintaining limited funding and staff for collaborative research

Beams: 40-200 MeV, 0.1 – 140 µA proton beams; Raster beam under development and due to be completed in FY 2016.

Additional Capabilities: Hot cell facilities for remote manipulation of intense sources, radiochemical characterization and separations, expertise in gamma-ray spectroscopy and thermal analysis of targets and machining of target material and cans.

Research Focus: Isotope production and R&D for radiochemical separations.

Contact person: Cathy Cutler: email: ccutler@bnl.gov Phone: +1 (631) 344-3873

Prepared by Suzanne V. Smith

This program uses the Brookhaven Linac Isotope Producer (BLIP), and the associated radiochemistry laboratory and hot cell complex in Building 801 to develop, prepare, and distribute to the nuclear medicine community and industry some radioisotopes that are difficult to produce or are not available elsewhere. The BLIP, built in 1972, was the world's first facility to utilize high-energy protons for radioisotope production by diverting the excess beam of the 200 MeV proton LINAC that injects protons into the Booster synchrotron for injection into the AGS then RHIC for the high energy nuclear physics program. After several upgrades BLIP continues to serve as an international resource for the production of selected isotopes that are generally unavailable elsewhere. The Linac is capable of accelerating H- ions to produce 66, 90, 118, 140, 162, 184 or 202 MeV protons at 37-48 mA current for 425 µs duration with a 6.67 Hz repetition rate. In 2015 FY, with the initial phase of the Linac Intensity Upgrade project complete, the Linac has reached currents of 142 µA. A hot-cell in building 931, situated over target area, is used to transfer the two target assembly boxes to and from the irradiation area. The target boxes can house up to four targets in each, however degraders can also be used to tune the beam to the desired energy on the target. AIP funded project to raster the proton beam will be completed in 2016. This upgrade will allow more heat sensitive targets to be irradiated at higher currents. BLIP operates usually concurrently with the RHIC polarized proton program and BLIP receives about 90% of the available beam pulses.

The irradiated targets are transported to Building 801, which contains chemical processing capabilities, which include Target Processing Facilities with 7 hot-cells with manipulators, one cold chemistry, 3 radiochemistry and an instrumentation laboratory. The latter laboratory has three gamma spectrometers and an ICP-OES and ICP-MS, set-up for the characterization of radioactive samples. Additional available research capabilities include four radiochemistry laboratories and 2-4 Hot-Cells. Other available instrumentation include a gamma counter, 5 fume hoods, HPLC, balances, centrifuges, glove boxes, machining capabilities and thermal analysis to target materials.

7.3 A.3: Brookhaven National Laboratory, Tandem Van De Graaff

General Description: A flexible and user-friendly facility for providing high quality ion beams for a variety of uses.

Beams: Two large 15 MeV electrostatic accelerators which deliver ion beams covering most of the periodic table

Please visit our website for additional information: https://www.bnl.gov/tandem/

Prepared by Dannie Steski

The Brookhaven National Laboratory Tandem Van de Graaff Facility consists of two 15-Megavolt Tandem Van de Graaffs (the largest operational electrostatic accelerators in North America). A wide range of ion species and energies (see table 1) are delivered to the users on a full cost-recovery basis, from 1 MeV protons to 337 MeV Gold ions. Applications include the study of radiation effects on electronics for space applications, calibration of particle detectors, radiobiology studies, production of track-etched filter material, superconductor enhancements and high energy ion implantation in semiconductors. Rapid energy and ion changes, well controlled intensities, accurate dosimetry, high quality beams and extraordinary reliability make this a very versatile user-friendly facility.

	Z	A	Max Energy (MeV)
Hydrogen	1	1	28.75
Helium	2	4	43.12
Lithium	3	7	57.2
Boron	5	11	85.5
Carbon	6	12	99.6
Oxygen	8	16	128
Fluorine	9	19	142
Magnesium	12	24	161
Silicon	14	28	187
Chlorine	17	35	212
Titanium	22	48	232
Chromium	24	52	245
Iron	26	56	259

Nickel	28	58	270
Copper	29	63	277
Germanium	32	72	273
Bromine	35	81	287
Niobium	41	93	300
Silver	47	107	313
Iodine	53	127	322
Gold	79	187	337

Table 1: Example of available Ion Species and maximum energies. Other ions available on demand.

Testing of Electronics for Space Applications

The Single Event Upset Test Facility (SEUTF) is available for the study of space radiation effects, in particular, Single Event Upset (SEU) Testing and Spacecraft Instrument Calibration. Ion beams of more than 50 ion species are provided over a wide range of energies and intensities. Our capabilities range from 1 MeV protons to 337 MeV Gold ions and Linear Energy Transfer (LET) in silicon from 0.01 to 91 MeV-cm^2/mg. The large, automated test chamber contains accurate dosimetry and a positioning stage (figure 1) with laser alignment to ensure proper exposure of electronic parts.

Figure 4: SEUTF test chamber and positioning stage

Ion Irradiation and Implantation

The BNL Tandems have been used to irradiate a wide variety of materials with heavy ions. A large diameter beam pipe and special chamber allow for large irradiation areas. Ion energies much higher than at most implanters allow a range of implantation depths not commonly available. Good dosimetry and fast energy changes result in efficient and accurate implantations.

One area of research is the enhancement of Superconductors. Implanting gold ions in superconducting wire can increase the critical current by a factor of four.

Another application that is of increasing interest is the implantation of silicon carbide (SiC) wafers (figure 2) with ions such as aluminum, boron, and nitrogen to maximum depths larger than 15 micrometers. Presently the implantation is done at room temperature, but a new facility is being built that will heat the SiC wafer to approximately 1000ºC during the implantation process.

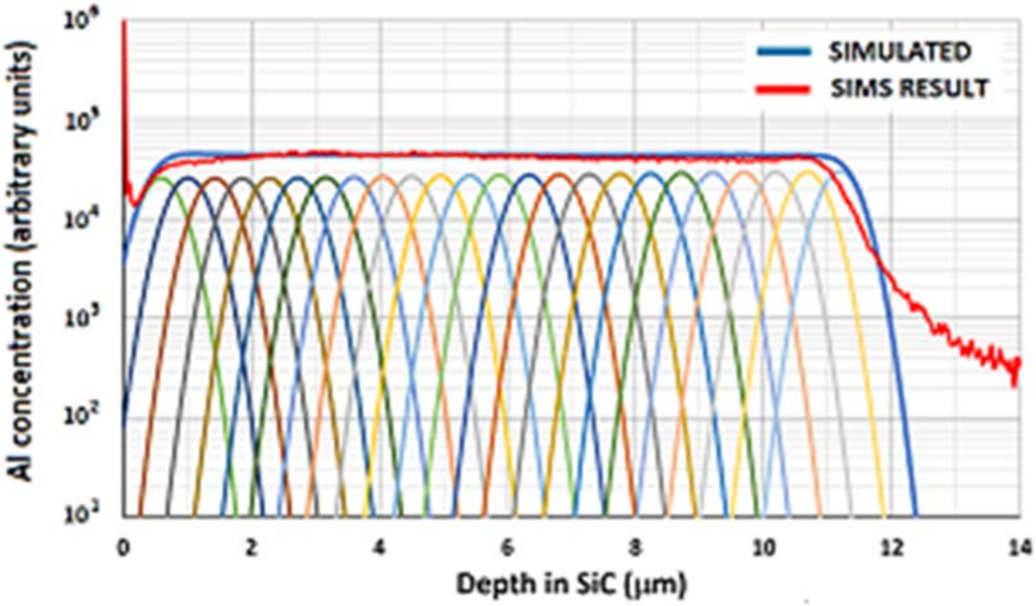
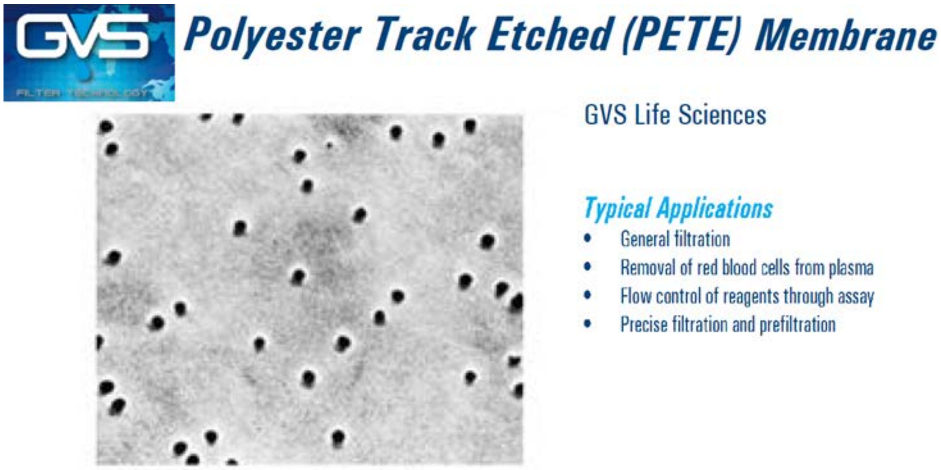


Figure 5: Simulation vs measured results of Al ions implanted in Silicon Carbide wafer

1. Fabricating Filter Materials

Plastic films used in the fabrication of nano- and micro-pore filters (figure 3) for ultra-pure water filtration and for specialized medical and biological applications are bombarded with heavy ions in a chamber owned by GE HealthCare. These materials are used in a large variety of medical tests, biology investigations, microchip tissue growth, fabrication, and find important applications.



Polyester Track Etched (PETE) Membrane

GVS Life Sciences

Typical Applications
- General filtration
- Removal of red blood cells from plasma
- Flow control of reagents through assay
- Precise filtration and prefiltration

Figure 6: Magnified view of micro-pore filter material.

Radiobiology Research Facility

Complementing the NASA Radiations Effects Facility (NSRL) at BNL, a lower ion energy radiobiology research facility (figure 4) at the Tandem has been developed. Low energies may be of particular interest since the high energy ions lose energy when traversing spacecraft materials and produce the maximum damage just before coming to rest in the astronauts' bodies. Thus, energies lower than most present in the primary cosmic ray spectrum are appropriate to cover the range of maximum LET (the Bragg peak) but, due to their short ranges, they are only useful to perform studies with thin samples such as cell cultures.

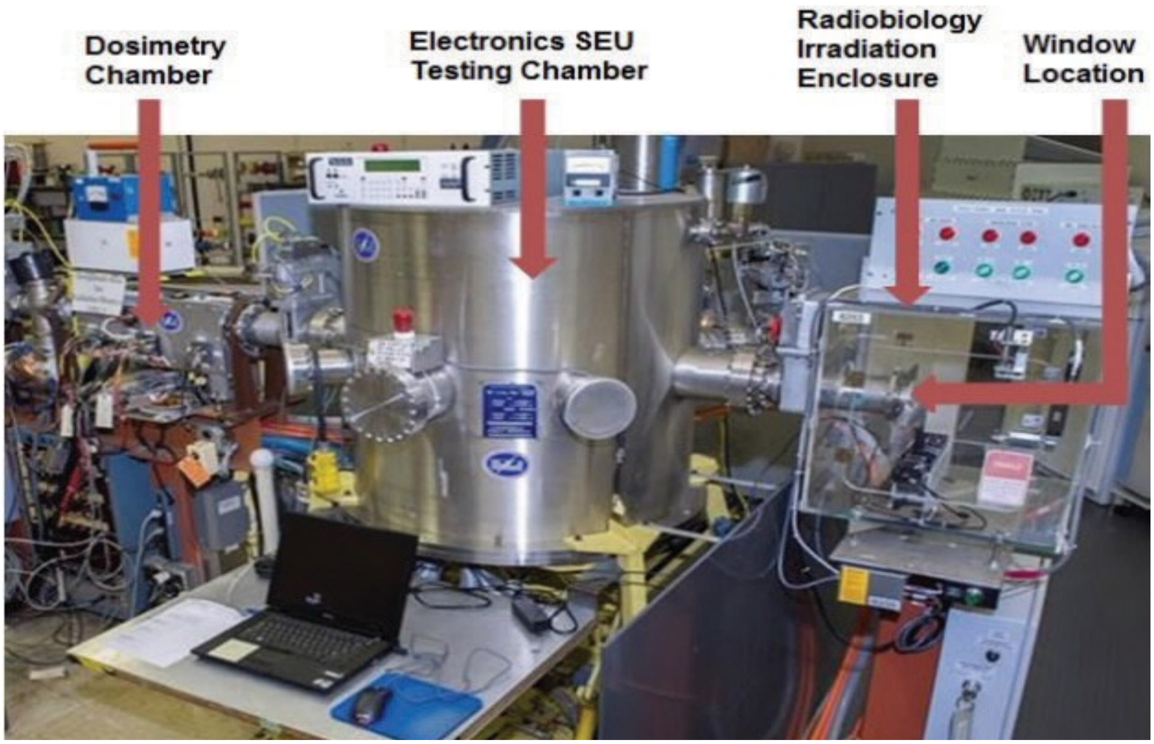


Figure 7: Radiobiology Irradiation enclosure to the left of the SEUTF chamber

Special Projects

Many important R&D projects have been carried out by users of the Tandem facility, including testing of electronic modules for the Mars Rovers, optical components of the Hubble Space Telescope and the effects of radiation on fiber optics, solar cells, and solar sails. Recently, dosimeters for the International Space Station and future manned space missions have been calibrated at the Tandem Van de Graaff.

For additional information visit https://www.bnl.gov/tandem/

7.4 A.4: Florida State University, John D. Fox Accelerator Laboratory

General Description: University Accelerator Laboratory; Research program driven by local faculty in collaboration with various university and laboratory groups

Accelerators: 9 MV Tandem, 8 MV Superconducting Linac

Beams: Stable beams of Masses 1-50, up to 4-8 MeV/u energy; Radioactive beams produced in-flight at RESOLUT facility, masses 6-30

Additional Capabilities: Compton-suppressed γ-detector array; ANASEN active target detector system; RESONEUT neutron detector setup
Soon: High-resolution high-acceptance magnetic spectrograph

Research Focus: Nuclear Structure studies using high-resolution γ-spectroscopy; Nuclear Astrophysics studies with radioactive and stable beams; Development of advanced detector systems for exotic beam experiments

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Prepared by I. Wiedenhöver

The John D. Fox laboratory operates a two-stage accelerator comprised of a 9 MV FN tandem accelerator and an 8 MV superconducting linear accelerator (Linac). The FN tandem is injected by either a NEC SNICS-II cesium sputter ion source, for most beams created from solid chemicals, or an NEC RF-discharge source for beams generated from gaseous materials, most importantly ^{3}He and ^{4}He. Among the beams available from the sputter source is the radioactive isotope ^{14}C.

Figure 9. The FSU Tandem accelerator

The beams from the Tandem are injected into the Linac, which more than doubles their energy. The superconducting linear accelerator consists of twelve accelerating resonators installed in three cryostats, plus buncher and re-buncher. The resonators are niobium-on-copper "split-ring" resonators produced by Argonne National Laboratory. The cryostats were designed and built at FSU.

The laboratory has developed an upgrade plan to increase the energy and mass-range of beams available for experiments. The upgrade entails the increase of cryogenic capacity by the addition of a second liquid Helium refrigerator (completed 2013), and the addition of two cryostats to the Linac.

A recent focus of the laboratory operations is on experiments with radioactive beams created in RESOLUT, an in-flight radioactive beam facility, which uses beams from the Tandem-Linac to create beams of exotic, radioactive isotopes. The isotopes, which are created through a nuclear reaction in the production target, are separated in mass by the combined effect of the electrical fields in a superconducting RF-resonator and the magnetic fields of the spectrograph.

The laboratory has developed advanced detector systems for research with radioactive beams. One example is the ANASEN device, which was developed in collaboration with a group from Louisiana State University. ANASEN is an active-target detector for the efficient study of resonances in exotic nuclei, either for nuclear structure or nuclear astrophysics. ANASEN will be used both at FSU and the re-accelerated beam facility of the NSCL.

The FSU laboratory is in the process of installing a high-resolution magnetic Split-Pole spectrograph, which had previously been used at the Yale Nuclear Structure Laboratory. The device is projected to be commissioned in the summer of 2016. The research with this device will focus on the spectroscopy of resonances for nuclear astrophysics.

Our group is one of the seven founding members of ARUNA, the Association for Research with University Nuclear Accelerators. ARUNA's goal is to support and enhance the research and education programs enabled by University laboratories.

For up to date information on the laboratory and its science program, visit http://fsunuc.physics.fsu.edu

7.5 A.5: Idaho National Laboratory

General Description:

- **ATR:** Fuels and materials test reactor
- **NRAD:** TRIGA® Mark II tank-type research reactor.
- **MANTRA program:** integral reactor physics experimental program to infer the neutron capture cross sections of actinides and fission products in fast and epithermal spectra.

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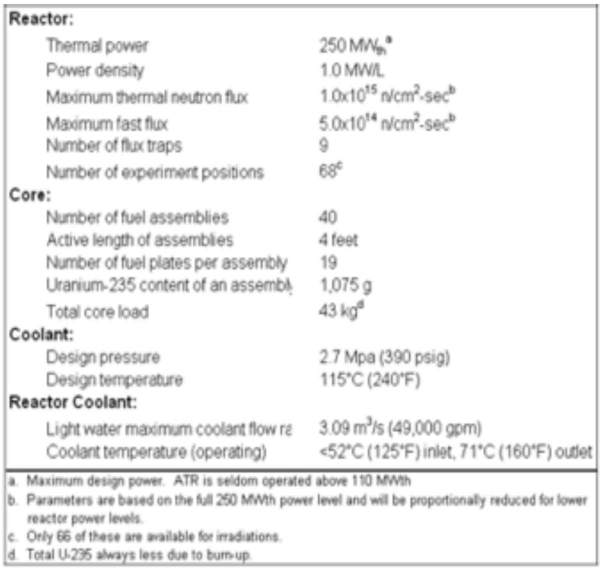
7.5.1 The Advanced Test Reactor (ATR)

The ATR is located at the ATR Complex on the INL site and has been operating continuously since 1967. The primary mission of this versatile facility was initially to serve the U.S. Navy in the development and refinement of nuclear propulsion systems. However, in recent years, the ATR has been used for a wider variety of government- and privately-sponsored research.

The designation of the ATR as a National Scientific User Facility (NSUF) provides nuclear energy researchers access to world-class facilities to support the advancement of nuclear science and technology. The ATR NSUF accomplishes this mission by offering state-of-the-art experimental irradiation testing and PIE facilities and technical assistance in design and safety analysis of reactor experiments. ATR general characteristics and some approximate irradiation performance data are summarized in Tables I and II, respectively.

The ATR has large test volumes in high-flux areas. Designed to permit simulation of long neutron radiation exposures in a short period of time, the maximum thermal power rating is 250 MWth with a maximum unperturbed thermal neutron flux of 1.0 x 1015 n/cm^2–s. Since most recent experimental objectives generally do not require the limits of its operational capability, the ATR typically operates at much lower power levels. Occasionally, some lobes of the reactor are operated at higher powers that generate higher neutron flux.



Reactor:	
Thermal power	250 MW$_{th}$^{a}
Power density	1.0 MW/L
Maximum thermal neutron flux	1.0x10^{15} n/cm^2-sec^b
Maximum fast flux	5.0x10^{14} n/cm^2-sec^b
Number of flux traps	9
Number of experiment positions	68^c
Core:	
Number of fuel assemblies	40
Active length of assemblies	4 feet
Number of fuel plates per assembly	19
Uranium-235 content of an assembl	1,075 g
Total core load	43 kg^d
Coolant:	
Design pressure	2.7 Mpa (390 psig)
Design temperature	115°C (240°F)
Reactor Coolant:	
Light water maximum coolant flow ra	3.09 m^3/s (49,000 gpm)
Coolant temperature (operating)	<52°C (125°F) inlet, 71°C (160°F) outlet

a. Maximum design power. ATR is seldom operated above 110 MWth
b. Parameters are based on the full 250 MWth power level and will be proportionally reduced for lower reactor power levels.
c. Only 66 of these are available for irradiations.
d. Total U-235 always less due to burn-up.

Table 2. ATR general characteristics.

The ATR is cooled by pressurized (2.5 MPa [360 psig]) water that enters the reactor vessel bottom at an average temperature of 52°C (125°F), flows up outside cylindrical tanks that support and contain the core, passes through concentric thermal shields into the open upper part of the vessel, then flows down through the core to a flow distribution tank below the core. When the reactor is operating at full power, the primary coolant exits the vessel at a temperature of 71°C (160°F).

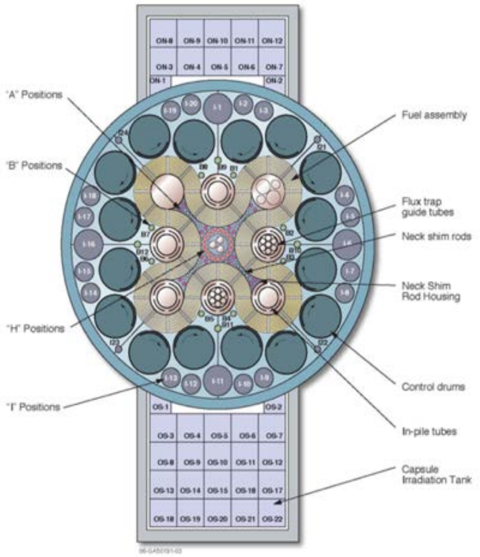
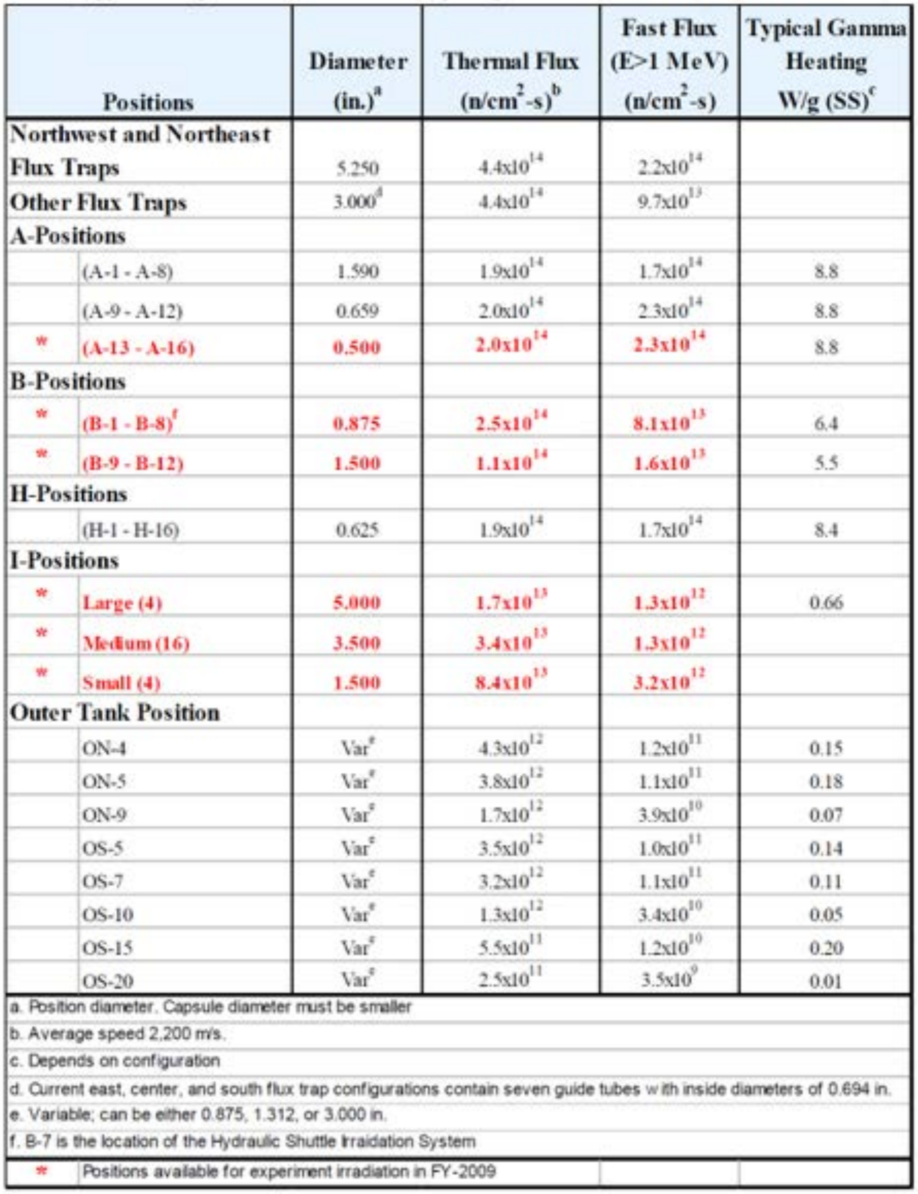


Figure 11. ATR Core cross section.

The unique design of ATR (Figure 11) control devices permits large power variations among its nine flux traps using a combination of control cylinders (drums) and neck shim rods. The beryllium control cylinders contain hafnium plates that can be rotated toward and away from the core, and hafnium shim rods, which withdraw vertically, can be individually inserted or withdrawn for minor power adjustments. Within bounds, the power level in each corner lobe of the reactor can be controlled independently to allow for different power and flux levels in the four corner lobes during the same operating cycle.

Neutron flux in the ATR varies from position to position and along the vertical length of the test position. It also varies with the power level in the lobe(s) closest to the irradiation position. Thermal and fast flux intensity values listed in Table 3 are at the core mid-plane for a reactor power of 110 MWth and assume a uniform reactor power of 22 MWth in each lobe.



Positions		Diameter (in.)[a]	Thermal Flux (n/cm^2-s)[b]	Fast Flux (E>1 MeV) (n/cm^2-s)	Typical Gamma Heating W/g (SS)[c]
Northwest and Northeast Flux Traps		5.250	$4.4x10^{14}$	$2.2x10^{14}$	
Other Flux Traps		3.000[d]	$4.4x10^{14}$	$9.7x10^{13}$	
A-Positions					
	(A-1 - A-8)	1.590	$1.9x10^{14}$	$1.7x10^{14}$	8.8
	(A-9 - A-12)	0.659	$2.0x10^{14}$	$2.3x10^{14}$	8.8
*	**(A-13 - A-16)**	**0.500**	**$2.0x10^{14}$**	**$2.3x10^{14}$**	8.8
B-Positions					
*	**(B-1 - B-8)[f]**	**0.875**	**$2.5x10^{14}$**	**$8.1x10^{13}$**	6.4
*	**(B-9 - B-12)**	**1.500**	**$1.1x10^{14}$**	**$1.6x10^{13}$**	5.5
H-Positions					
	(H-1 - H-16)	0.625	$1.9x10^{14}$	$1.7x10^{14}$	8.4
I-Positions					
*	**Large (4)**	**5.000**	**$1.7x10^{13}$**	**$1.3x10^{12}$**	0.66
*	**Medium (16)**	**3.500**	**$3.4x10^{13}$**	**$1.3x10^{12}$**	
*	**Small (4)**	**1.500**	**$8.4x10^{13}$**	**$3.2x10^{12}$**	
Outer Tank Position					
	ON-4	Var[e]	$4.3x10^{12}$	$1.2x10^{11}$	0.15
	ON-5	Var[e]	$3.8x10^{12}$	$1.1x10^{11}$	0.18
	ON-9	Var[e]	$1.7x10^{12}$	$3.9x10^{10}$	0.07
	OS-5	Var[e]	$3.5x10^{12}$	$1.0x10^{11}$	0.14
	OS-7	Var[e]	$3.2x10^{12}$	$1.1x10^{11}$	0.11
	OS-10	Var[e]	$1.3x10^{12}$	$3.4x10^{10}$	0.05
	OS-15	Var[e]	$5.5x10^{11}$	$1.2x10^{10}$	0.20
	OS-20	Var[e]	$2.5x10^{11}$	$3.5x10^{9}$	0.01

a. Position diameter. Capsule diameter must be smaller

b. Average speed 2,200 m/s.

c. Depends on configuration

d. Current east, center, and south flux trap configurations contain seven guide tubes with inside diameters of 0.694 in.

e. Variable; can be either 0.875, 1.312, or 3.000 in.

f. B-7 is the location of the Hydraulic Shuttle Irraidation System

* Positions available for experiment irradiation in FY-2009

Table 3. Approximate peak flux values for ATR capsule positions at 110 MWth (22 MWth in each lobe).

7.5.2 Neutron Radiography Reactor (NRAD)

The neutron radiography (NRAD) reactor is a TRIGA® (Training, Research, Isotopes, General Atomics) Mark II tank-type research reactor located in the basement, below the main hot cell, of the Hot Fuel Examination Facility (HFEF) at the Idaho National Laboratory (INL). It is equipped with two beam tubes with separate radiography stations for the performance of neutron radiography irradiation on small test components.

The NRAD reactor is currently under the direction of the Battelle Energy Alliance (BEA) and is operated and maintained by the INL and Hot Cell Services Division. It is primarily used for neutron radiography analysis of both irradiated and un-irradiated fuels and materials. Typical applications for examining the internal features of fuel elements and assemblies include fuel pellet separations, fuel central-void formation, pellet cracking, evidence of fuel melting, and material integrity under normal and extreme conditions.

The NRAD core is designed for steady-state operation with or without in-core and/or in-tank experiments. The combined reactivity worth of all removable experiments within the reactor tank is limited to less than \$0.50.

The NRAD reactor is a TRIGA-conversion-type reactor originally located at the Puerto Rico Nuclear Center (PRNC). It was converted to a TRIGA-FLIP-(Fuel Life Improvement Program)-fueled system (70% 235U) in 1971. The 2-MW research reactor was closed in 1976 and then a portion of the TRIGA reactor fuel elements and other components (with a single radiography beam line) were moved in 1977 by the US Department of Energy (DOE) to Argonne National Laboratory (West) in Idaho Falls, Idaho. The NRAD reactor was first brought to critical in October 1977, and then became operational in 1978. A second beam line was added in 1982.

The NRAD reactor (Figure 12) is a 250 kW TRIGA LEU conversion reactor that is a water-moderated, heterogeneous, solid-fuel, tank-type research reactor. The reactor is composed of fuel in three- and four element clusters that can be arranged in a variety of lattice patterns, depending on reactivity requirements. The grid plate consists of 36 holes, on a 6-by-6 rectangular pattern, that mate with the end fittings of the fuel cluster assemblies.

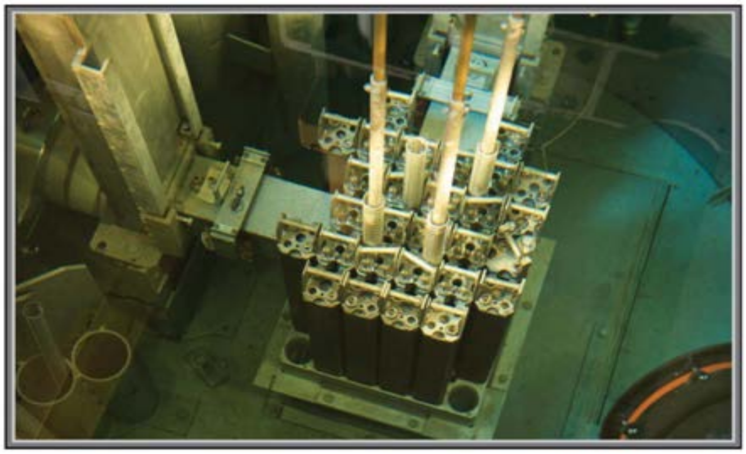


Figure 12. In-tank view of the NRAD reactor core.

The NRAD LEU core configuration contains 60 fuel elements, two water-followed shim control rods, and one water-followed regulating rod (Figure 3). A water hole is provided as an experimental irradiation position. The NRAD reactor uses graphite neutron reflector assemblies located along the periphery grid plate locations. The number and position of fuel-element and reflector assemblies can be varied to adjust core reactivity.

7.5.3 MANTRA Program

The MANTRA (Measurements of Actinide Neutron Transmutation Rates with Accelerator mass spectrometry) experimental program is the first reactor physics integral experiment performed in the USA in more than 20 years. It aims at obtaining integral information about neutron cross sections for actinides that are important for advanced nuclear fuel cycles. Its principle is to irradiate very pure actinide samples in the Advanced Test Reactor (ATR) at INL and, after a given time, determine the amount of the different transmutation products. The determination of the nuclide densities before and after neutron irradiation allows inference of the effective neutron capture cross-sections. The following actinides have been irradiated: ^{232}Th, ^{233}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{244}Pu, ^{241}Am, ^{243}Am, ^{244}Cm and ^{248}Cm. The irradiated fission products are: ^{149}Sm, ^{153}Eu, ^{133}Cs, ^{103}Rh, ^{101}Ru, ^{143}Nd, ^{145}Nd and ^{105}Pd. In order to obtain effective neutron capture cross sections corresponding to different neutron spectra, three sets of actinide samples were irradiated: the first one is filtered with cadmium and the other two are filtered with enriched boron of different thicknesses (5 mm and 10 mm). The neutron capture reactions on ^{10}B and ^{113}Cd have large cross-sections and strongly impact the neutron spectrum (see Figure 13) allowing the samples to be irradiated in epithermal and fast neutron spectra whereas the unfiltered neutron spectrum is largely thermal. The total flux levels in the samples are, respectively, about 2×10^{14} n/cm^{2}s and 10^{14} n/cm^{2}s with the cadmium filter and the boron filters. The cadmium-filtered and the 5 mm boron-filtered irradiations were completed in January 2013 after, respectively, 55 days and 110 days in the reactor. The last irradiation with the 10 mm boron-filtered was completed in January 2014 after 110 days in the reactor.

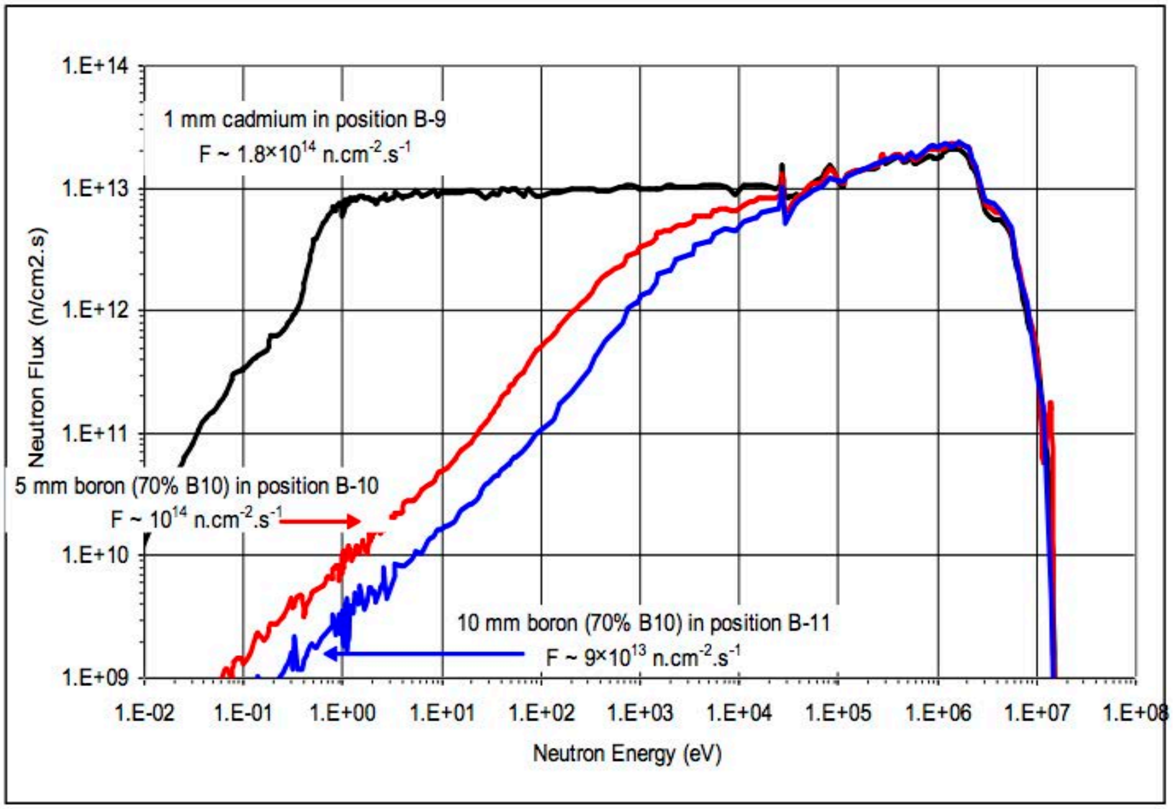


Figure 13. Neutron flux in the samples with boron and cadmium filters as calculated with MCNP.

The Post Irradiation Examination (PIE) was carried out both at INL and ANL using, respectively, the newly acquired Multi-Collector ICPMS and the Accelerator Mass Spectrometry at the ATLAS facility. The use of these two independent measurement techniques is benefiting both the reactor physicists interested in the neutron cross sections, by providing them with two sets of independent measurements, and also the experimentalists in charge of both facilities, by providing them with a consistent benchmark of their respective techniques. The results of detailed MCNP calculations are currently being compared with the measured isotopic ratio present in the irradiated samples.

Even though we expect the MANTRA experimental program to be a success, there is already a need for a second phase (MANTRA-2) of such a type of experiments. There are good reasons justifying this statement. First there are several actinide samples that, for different reasons, have not been irradiated, specifically ^{238}Pu, ^{241}Pu, and ^{241}Cm (irradiated only with thin filters). Moreover, at the time of an anticipated MANTRA-2 campaign efficient mass separators should be available at INL. This would allow purifying samples of isotopes already irradiated in MANTRA and avoiding one of the program's main concerns: contamination from other isotopes during post irradiation analysis.

Finally, due to the limited space available, in most cases only one sample per isotope (and in a couple of cases two) was irradiated in MANTRA. For the sake of comparison: in the French irradiation experiments PROFIL at least three, in PROFIL-2 even six samples of the same isotope were irradiated. This approach is justified by the fact that in certain cases during the post irradiation analysis, and due to bad manipulation, some samples may become contaminated. While for MANTRA, a low failure rate is expected, a MANTRA-2 campaign would provide the opportunity for repeating the compromised irradiation of the respective isotopes.

In complementing the MANTRA campaign, a separate experimental program performed at the NRAD facility would provide a wealth of integral experimental data in support of nuclear data validation and uncertainty quantification efforts. The INL NRAD is a TRIGA reactor that has enough space to allow the introduction of thick neutron filters (including ^{238}U blocks) allowing simulating the full gamut of neutron spectra from thermal, epithermal, soft fast, to hard fast. The systematic measurement of fission rate spectral indices using fission micro-chamber would enhance the knowledge on a vast range of actinides (both major and minor). Moreover, in this facility reactivity sample oscillation measurements could be performed with the help of an Idaho State University (ISU) apparatus (open and closed loop) that could be easily installed at NRAD. These measurements of actinides samples in different spectra would be invaluable for the validation and uncertainty quantification of cross sections needed for advanced fuel cycles analyses.

7.6 A.6: University of Kentucky Accelerator Laboratory

General Description: University facility with research programs in nuclear structure, neutron-induced reactions, and neutron cross section measurements

Accelerator: 7-MV Van de Graaff Accelerator

Beams: pulsed beams with high currents of light ions (protons, deuterons, ^{3}He, and ^{4}He ions); secondary neutrons

Experimental focus: neutron scattering reactions with neutron time-of-flight and gamma-ray detection

Present detector array capabilities: HPGe gamma-ray detectors and various neutron detectors

Contact person: Steven W. Yates, yates@uky.edu, 859-257-4005

Prepared by Steven W. Yates and Erin E. Peters

The University of Kentucky Accelerator Laboratory (UKAL) is one of the premier facilities for studies with fast (MeV) neutrons. The laboratory opened in 1964 and the accelerator underwent a major upgrade in the 1990's. Over the last 5 decades, the facilities have been used for research in nuclear physics, as well as for homeland security and corporate applications.

The UK 7-MV single-stage model CN Van de Graaff accelerator is capable of producing pulsed beams of protons, deuterons, ^{3}He, and ^{4}He at energies up to 7 MeV. The beam is pulsed at a frequency of 1.875 MHz and can also be bunched in time such that each pulse has a FWHM of ≈1 ns. Secondary neutron fluence may also be produced by reaction of protons or deuterons with tritium or deuterium gas. Nearly monoenergetic neutrons with energies between ≈ 0.1 – 23 MeV may be produced with fluxes up to 10^9 neutrons/s depending on the reaction employed. The pulsed beam allows for use of time-of-flight methods. Both neutron and gamma-ray detection are available. Figure 1 shows the typical setup for neutron detection. For more detailed information, see Refs. [1] and [2].

The research performed at the UKAL has been funded continuously by the U. S. National Science Foundation for more than 50 years and includes fundamental science studies of nuclear structure and reactions. In recent years, the laboratory has also received funding from the U. S. Department of Energy in support of a more application-based project for neutron cross section measurements.

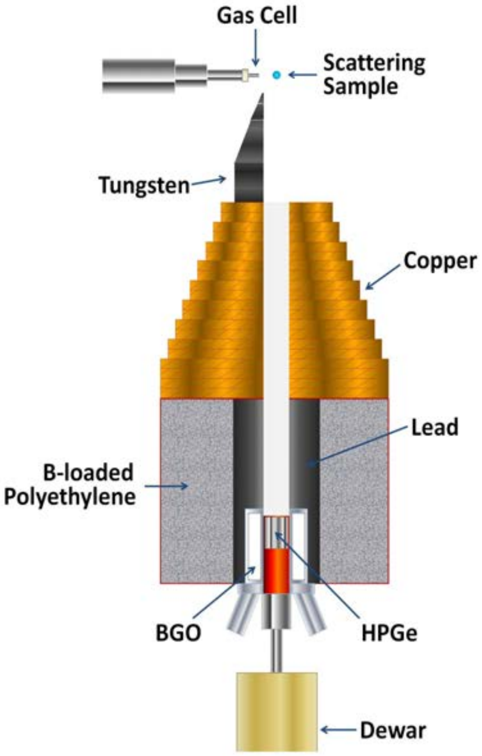


Figure 14. Typical experimental setup for neutron time-of-flight measurements.

Figure 15. Comparison of 4.00-MeV elastic scattering cross sections for ^{23}Na with those from various nuclear libraries [2].

The Advanced Fuels Program of the Department of Energy sponsors research and development of innovative next generation light water reactor (LWR) and future fast systems. Input needed for both design and safety considerations for these systems includes neutron elastic and inelastic scattering cross sections that impact the fuel performance during irradiations, as well as coolants and structural materials. The goal of this project is to measure highly precise and accurate nuclear data for elastic/inelastic scattered neutrons. The high-precision requirements identified in the campaign supported by nuclear data sensitivity analyses have established a high priority need for precision elastic/inelastic nuclear data on the coolant ^{23}Na and the structural materials ^{54}Fe and ^{56}Fe. Measurements of cross sections over an energy region from 1 to 9 MeV are desired. The measurements for ^{23}Na were recently published [2] and example data are shown in Figure 15; measurements for the stable iron isotopes are in progress. The major theme of this applied science program is affirming the accuracy of the recommended cross sections found in the nuclear libraries, such as ENDF, JENDL, and JEFF and generating additional data where none exists. Often, the discrepancy between library values is greater than the covariance implies for the individual libraries. In other situations, the measured data on which the libraries are based is simply non-existent.

Gamma-ray production cross sections are also of interest for neutrinoless double-beta decay (0νββ). The experimental signature of 0νββ is a discrete peak at the energy of the Q value of the decay. It is possible that neutrons may inelastically scatter from surrounding materials or those composing the detector and produce background gamma rays in the region of the Q value, which would obscure the observation of this speculated but as yet unobserved process. Experiments have been performed to identify and measure cross sections for such background gamma rays for the 0νββ candidates ^{76}Ge [4] and ^{136}Xe [5].

Other applications-based programs have been established with collaborators from multiple institutions who are interested in detector development and/or characterization. Groups from the University of Guelph, the University of Nevada Las Vegas, and the University of Massachusetts at Lowell have all performed experiments which utilize the monoenergetic neutron capabilities in order to perform detector tests and characterizations. The Guelph group characterized deuterated benzene liquid scintillators, which will now be employed in the DESCANT array at TRIUMF [3].

Scientists with commercial interests, for example, Radiation Monitoring Devices in Watertown, MA, also visit the laboratory to make use of the monoenergetic neutrons. Projects range from development of radiation detecting materials to imaging systems. In addition to the typical nuclear physics markets, their detection systems are deployed in medical diagnostic, homeland security, and industrial non-destructive testing applications.

See the laboratory web page at http://www.pa.uky.edu/accelerator/ for an expanded description of the facilities, the research programs, and recent results from UKAL.

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7.7 A.7: Lawrence Berkeley National Laboratory 88-Inch Cyclotron

General Description:
- 88-Inch Cyclotron: Sector-focused K-150 cyclotron coupled to 3 ECR ion sources

Beams: Protons to uranium @ $E/A \leq 20$ MeV/amu; neutrons @ $E_n \leq 60$ MeV; Beam power to 1.5 kW

Additional Capabilities: BGS recoil separator, FIONA, GENESIS, FLUFFY

Research Focus: Heavy element nuclear structure; Nuclear Data; Space Effects

Contact person: Cyclotron Director: Larry Phair (LWPhair@lbl.gov); USNDP Contact: Lee Bernstein (LABernstein@berkeley.edu)

Website(s): https://cyclotron.lbl.gov
https://nucleardata.berkeley.edu

Prepared by LA. Bernstein and L.W. Phair

7.7.1 Executive Summary

The 88-Inch Cyclotron (the "88") at Lawrence Berkeley National Laboratory (LBNL) is a variable energy, high-current, multi-particle cyclotron capable of accelerating ions ranging from protons to uranium at energies approaching and exceeding the Coulomb barrier. Maximum currents on the order of 10 particle•µamperes, with a maximum beam power of 1.5 kW, can be extracted from the machine for use in experiments in 7 experimental "caves". Beam currents up to the mA level could also be developed through the use of internal ion sources and targets. In addition to single-isotope beams the cyclotron can produce mixed-ion "cocktail" beams for use in electronic upset and damage studies. The cyclotron can also produce high-intensity pulsed, neutron beams whose energy can be determined via time-of-flight with flux $\leq 10^7$ n/s/cm^2 (DE/E≈5% at E_n=10 MeV), or broad spectrum (DE/E≈50%) with flux up to $\leq 10^{13}$ n/s/cm^2 via thick target deuteron breakup. A description of the 88-Inch cyclotron can found in the paper by *Kireeff-Covo* [Kir18].

The cyclotron also has an array of research equipment developed for heavy-element research including the Berkeley Gas-filled Separator (BGS) and the FIONA ion trap. Lastly, a wide variety of mobile neutron, particle and gamma-ray detectors together with a mobile data acquisition system are present at the cyclotron for use in user experiments.

7.7.2 General Considerations of 88-Inch Cyclotron

The 88 was originally envisioned as a high-current, variable energy, light-ion accelerator for nuclear physics and nuclear chemistry studies, as well as for the production of isotopes used in scientific research. It started operation in 1961 and has maintained its position as a premier stable-beam facility through periodic upgrades, especially to its ion sources [Lei06]. These ion sources have enabled acceleration of an ever-increasing variety of heavy-ion beams up to, and beyond, the Coulomb barrier. Protons, deuterons, and alpha particle beams are available up to maximum energies of 55, 65, and 130 MeV, respectively. For extracted beams the operational upper limits of current intensities are not known since we restrict running to a maximum power of 1.5 kW. These administrative limitations are self-imposed. There is no reason that we cannot exceed these restrictions with proper planning and preparation. One can readily envision extracted beams of several tens of particle-microamperes. Development of a negative ion acceleration scheme combined with “stripping” would allow a clean extraction of intense proton beams (as recently demonstrated with the same cyclotron at Texas A&M University).

One consideration for even more intense beams of light ions is the use of internal targets. Indeed, this technique was used at the 88 in its early years to produce isotopes for research and there is no reason that the capability cannot be re-established. This would enable use of beams with intensities exceeding a milliampere (1000μA). This would open up great possibilities for production of isotopes. But then radioactive target handling and radiochemistry would need additional attention. The resulting power levels (tens of kW) make it the only charged particle accelerator facility currently in the DOE complex capable of large-scale isotope production using light-ion beams other than protons.

Beam-time at the 88-Inch cyclotron can be obtained either via purchase (≈$2000/hour), or by merit-based review provided by a local advisory committee. Approximately 60% of the beam-time is reserved for nuclear science research, including the local nuclear data group[37]. Individuals interested in performing experiments at the 88-Inch should contact the user liaison, Mike Johnson (MBJohnson@lbl.gov), the cyclotron Larry Phair (LWPhair@lbl.gov) or the scientific director Paul Fallon (PFallon@lbl.gov).

7.7.3 Instrumentation and facility layout

The 88-Inch Cyclotron is host to a number of unique instruments and capabilities. These include three electron cyclotron resonance (ECR) ion sources, featuring VENUS, the most powerful superconducting ECR ion source in the world. These ECRs provide a range of highly-charged ions up to and including fully-stripped U^{92+}. The cyclotron also plays host to the Berkeley Gas-filled Separator (BGS). The BGS provides rejection of beam-like and fission fragment nuclides formed in heavy-ion reactions in excess $1:10^{12}$ for use in heavy-element research. The back end of the BGS can accommodate an array of pixelated Micron “W2” Si detectors three “Clover” HPGe detectors for use in alpha- and gamma-decay spectroscopy of evaporation product nuclides. Alternatively, the back end of the BGS can be coupled to the FIONA ion trap that can isolate a single charge-to-mass ratio fragment.

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[37] https://nucleardata.berkeley.edu

The 88-Inch cyclotron is capable of producing intense neutron beams using thick target deuteron breakup [Har18]. These beams can be used for both neutron scattering cross section measurements as well as Isotope Production [Mor23]. The Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering (GENESIS)[38] which can provide energy and angle differential neutron and gamma ray cross sections, supporting the (n,x) data initiative described in section 2.8. GENESIS directly supports nuclear reaction evaluation efforts described in section 2.2 of this report since inelastic scattering cross sections play a critical role in modeling nuclear systems undergoing fission, and the current nuclear data assessments disagree on the balance between elastic and inelastic cross section necessitating modern differential measurement.

LBNL also has a “Rabbit” system that allow for samples to be transferred rapidly from neutron irradiation locations to locations where decay radiation can be measured. The Fast Loading Unloading Facility for Fission Yields (FLUFFY)[39] at LBNL allows the rapid transport (≤0.7 s) of a capsule containing target samples between a neutron beam and an HPGe clover array. The rapidity of this transport allows measurement of short-lived fission product yields when an actinide sample is loaded in the capsule. These fission product yield and gamma-decay measurements support both the fission and accelerated decay data initiative described in sections 2.6 and 2.7 of this report respectively.

Lastly, the 88-Inch cyclotron can also be used to perform isotope production cross section measurements using charged particle beams and the stacked target technique [Mor20] as well as neutron activation [Mor23].

Taken together, these high- and low-energy neutron sources provide a more complete “toolkit” for addressing (n,x) nuclear data needs.

Figure 7.7.1 below shows the layout of the experimental capabilities at the cyclotron.

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[38] https://nucleardata.berkeley.edu/projects/genesis.html

[39] https://nucleardata.berkeley.edu/projects/fluffy.html

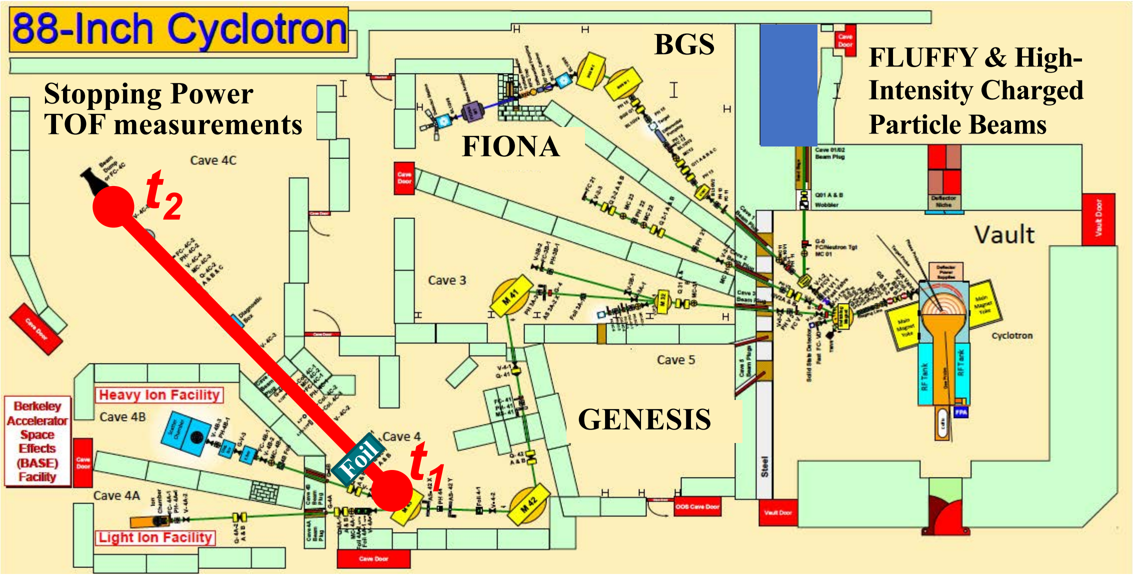

Figure 7.7.1. Experimental facility layout at the LBNL 88-Inch cyclotron showing the locations of (clockwise, starting at the top left) heavy-ion stopping power measurements, BGS+FIONA, FLUFFY and charged particle cross section measurements and the GENESIS array.

7.7.4 The Berkeley Accelerator Space Effects (BASE) facility

The table 7.7.1 lists the properties and constituents of these cocktail beams.

In addition to neutron and single-species ion beams, the 88-Inch cyclotron houses the Berkeley Accelerator Space Effects (BASE) facility that uses "cocktail" beams of heavy ions with similar cyclotron frequencies to uniformly dose electronics for Single Event Effects (SEE) electronics damage testing. These beams provide a unique possibility to address deficiencies in charged particle stopping powers for detector design, ion beam therapy and space exploration described in section 2.8.

The LBNL 88-Inch Cyclotron. Cocktail beams[40] with E/A of 4.5, 10, 16, 20 and 30 MeV/nucleon, $5 \leq Z \leq 79$ and $10 \leq A \leq 197$ would be extracted from the cyclotron and sent along a fixed path length between two sensors located at positions t_1 and t_2 with a differential thickness degrader located immediately after position t_1 at the location labeled "Foil". Beamtime for these experiments, including development time for the time-of-flight set-up, could be supported either by DOE/NP or by the BASE partner organizations. Similar capabilities also exist or are under development at Texas A&M university as well.

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[40] https://cyclotron.lbl.gov/base-rad-effects/heavy-ions/cocktails-and-ions

Table 7.7.1. BASE Facility Standard “Cocktail” Ion List. Standard “cocktails” (of species with similar charge-to-mass ratios) are listed along with their energy loss and range values.

Ion	**Cocktail** (AMeV)	**Energy** (MeV)	**Z**	**A**	**Chg. State**	**% Nat. Abund.**	**LET 0°**	**LET 60°**	**Range (Max)** (µm)
							(MeV/mg/cm2)		
B	**4.5**	44.90	5	10	+2	19.9	**1.65**	3.30	78.5
N	**4.5**	67.44	7	15	+3	0.37	**3.08**	6.16	67.8
Ne	**4.5**	89.95	10	20	+4	90.48	**5.77**	11.54	53.1
Si	**4.5**	139.61	14	29	+6	4.67	**9.28**	18.56	52.4
Ion	**Cocktail** (AMeV)	**Energy** (MeV)	**Z**	**A**	**Chg. State**	**% Nat. Abund.**	**LET 0°**	**LET 60°**	**Range (Max)** (µm)
Ar	**4.5**	180.00	18	40	+8	99.6	**14.32**	28.64	48.3
V	**4.5**	221.00	23	51	+10	99.75	**21.68**	43.36	42.5
Cu	**4.5**	301.79	29	63	+13	69.17	**29.33**	58.66	45.6
Kr	**4.5**	378.11	36	86	+17	17.3	**39.25**	78.50	42.4
Y	**4.5**	409.58	39	89	+18	100	**45.58**	91.16	45.8
Ag	**4.5**	499.50	47	109	+22	48.161	**58.18**	116.36	46.3
Xe	**4.5**	602.90	54	136	+27	8.9	**68.84**	137.68	48.3
Tb	**4.5**	724.17	65	159	+32	100	**77.52**	155.04	52.4
Ta	**4.5**	805.02	73	181	+36	99.988	**87.15**	174.30	53.0
Bi*	**4.5**	904.16	83	209	+41	100	**99.74**	199.48	52.9
B	**10**	108.01	5	11	+3	80.1	**0.89**	1.78	305.7
O	**10**	183.47	8	18	+5	0.2	**2.19**	4.38	226.4
Ne	**10**	216.28	10	22	+6	9.25	**3.49**	6.98	174.6
Si	**10**	291.77	14	29	+8	4.67	**6.09**	12.18	141.7
Ar	**10**	400.00	18	40	+11	99.6	**9.74**	19.48	130.1
V	**10**	508.27	23	51	+14	99.75	**14.59**	29.18	113.4
Cu	**10**	659.19	29	65	+18	30.83	**21.17**	42.34	108.0
Kr	**10**	885.59	36	86	+24	17.3	**30.86**	61.72	109.9

Y	**10**	928.49	39	89	+25	100	**34.73**	69.46	102.2
Ag	**10**	1039.42	47	107	+29	51.839	**48.15**	96.30	90.0
Xe	**10**	1232.55	54	124	+34	0.1	**58.78**	117.56	90.0
Au *	**10**	1955.87	79	197	+54	100	**85.76**	171.52	105.9
He*	**16**	43.46	2	3	+1	0.000137	**0.11**	0.22	1020.0
N	**16**	233.75	7	14	+5	99.63	**1.16**	2.32	505.9
O	**16**	277.33	8	17	+6	0.04	**1.54**	3.08	462.4
Ne	**16**	321.00	10	20	+7	90.48	**2.39**	4.78	347.9
Si	**16**	452.10	14	29	+10	4.67	**4.56**	9.12	274.3
Ion	**Cocktail** (AMeV)	**Energy** (MeV)	**Z**	**A**	**Chg. State**	**% Nat. Abund.**	**LET 0°**	**LET 60°**	**Range (Max)** (µm)
Cl	**16**	539.51	17	35	+12	75.77	**6.61**	13.22	233.6
Ar	**16**	642.36	18	40	+14	99.600	**7.27**	14.54	255.6
V	**16**	832.84	23	51	+18	99.750	**10.90**	21.80	225.8
Cu	**16**	1007.34	29	63	+22	69.17	**16.53**	33.06	190.3
Kr	**16**	1225.54	36	78	+27	0.35	**24.98**	49.96	165.4
Xe*	**16**	1954.71	54	124	+43	0.1	**49.29**	98.58	147.9
N	**30**	425.45	7	15	+7	0.370	**0.76**	1.52	1370.0
O	**30**	490.22	8	17	+8	0.04	**0.98**	1.96	1220.0
Ne	**30**	620.00	10	21	+10	0.27	**1.48**	2.96	1040.0
Ar	**30**	1046.11	18	36	+17	0.337	**4.87**	9.74	578.1

Additionally, BASE is unique in having beams parallel enough to support microbeams, used to probe increasingly miniaturized semiconductor parts with new modes of failure. The National Security Space (NSS) community and researchers from other government, university, commercial, and international institutions use these beams to understand the effect of radiation on microelectronics, optics, materials, and cells. Space missions utilizing the BASE Facility include Voyager, the Space Shuttle, Solar Dynamics Observatory, Mars Spirit and Opportunity rovers, Galileo (Jupiter), Cassini (Saturn), and the new James Webb Space Telescope.

7.8 A.8: Lawrence Livermore National Laboratory, National Ignition Facility (NIF)

Lawrence Livermore National Laboratory

General Description: The National Ignition Facility is a laser based internal confinement fusion facility. The NIF experimental facility has achieved total energy output of 1.3 MJ from a single ICF shot. It can be used to create high energy density (HED) environments that are unique and allow nuclear science regimes not achievable at other facilities.

Accelerator: NIF consists of 192 laser beams with high energy (>MJ) and ns-long pulses used to heat the interior of a cylindrical hohlraum to extremely hot temperatures (3.5 million K). The resultant x-ray photons ablate the surface of a 2 mm spherical target. The target is filled with DT fuel which is compressed by a factor of 20-40 which causes part of the fuel to undergo D(T,n) thermonuclear fusion.

Radiation Output:

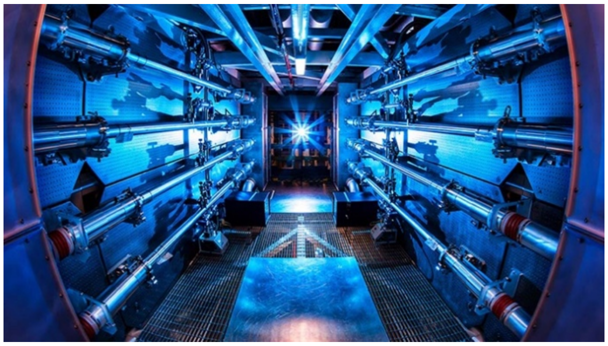
- NIF has been demonstrated to have the ability to output $>10^{17}$ 14 MeV neutrons in a single shot.
- Deuterium-deuterium (DD) fuel enables production of 2.45 MeV neutrons if desired

Experimental focus: NIF's main goal is achieving nuclear fusion. It has the largest short-pulsed (ps) 14 MeV neutron flux of any facility. The HED environment created allows stellar-like conditions for measurements of astrophysical relevant cross sections, and the large neutron flux allows for measurements of neutron-induced cross sections with very small amounts of target materials ($\sim 10^{13}$ atoms).
https://doi.org/10.1088/1361-6471/aa8693

Diagnostics: The NIF has a series of diagnostics for assessing the implosion and neutron yields, such as x-ray imaging, bang-time measurements, neutron imaging, nuclear yield, and spectrum diagnostics.

Contact person: John Despotopulos, despotopulos1@llnl.gov , (925) 422-7146 https://lasers.llnl.gov/

The NIF is a laser-based internal confinement fusion (ICF) facility located at B581. It produces neutrons from compression of capsules containing deuterium-tritium (DT) gas or solid mixtures. Both dedicated and ride-along nuclear science experiments [1] are possible under unique high energy density (HED) environments. The NIF has a series of diagnostics for assessing the implosion and neutron yields, such as x-ray imaging, bang-time measurements, neutron imaging, nuclear yield, and spectrum diagnostics. There also exists specialized diagnostics for neutron-induced reaction measurements, the Solid Radio-chemistry (SRC) di-agnostic for collection of solid debris and the Radio-chemical Analysis of Gaseous Species (RAGS) system for collection of gaseous reaction products.



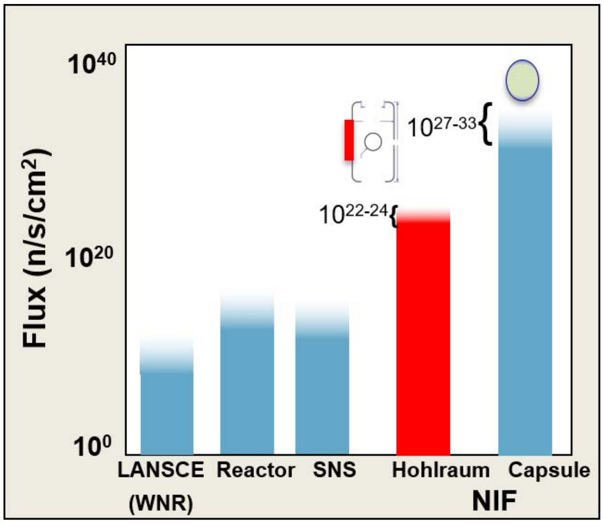


Figure 1:(top) Inside the NIF. (right) Comparison of neutron sources and relative intensities.

[1] D. Lonardoni, *et al.*, “First measurement of the ^{10}B(α,n)^{13}N reaction in an inertial confinement fusion implosion at the National Ignition Facility” (2021) (arXiv:2111.10213v2)

7.9 A.9: Lawrence Livermore National Laboratory, Inherently Safe Subcritical Assembly Facility

General Description: The Inherently Safe Subcritical Assembly (ISSA) is a subcritical water tank assembly with up to nine unirradiated Materials Test Reactor (MTR)-type highly enriched uranium fuel elements with a peak neutron multiplication of 20 (keff of 0.95). Lower multiplications can be achieved with lower fuel loadings. Experiments can be conducted with an external neutron source (e.g. C252, AmBe), neutron generator, or intrinsic source (alpha, n and spontaneous fission from the fuel).

ISSA has been benchmarked in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) as FUND-LLNL-ALPHAN-HE3-MULT-001 and has shown to be useful in validation of FREYA.

Experimental focus:

- Subcritical multiplicity experiments
- Active interrogation experiments
- Training in approach to critical methodology

Detector arrays: He3, could accommodate others (gamma, neutron)

Contact person: David Heinrichs, heinrichs1@llnl.gov, (925) 424-5679

The Inherently Safe Subcritical Assembly (ISSA), located at B255, offers the capability to conduct experiments for evaluation as a fundamental physics benchmark [1]. Benchmark experiments are used by nuclear criticality safety practitioners and nuclear data evaluators to validate radiation transport software and nuclear reaction cross section data libraries. Neutron detectors will measure neutron counts coming from the assembly as a function of time. By modeling ISSA and the detectors in a radiation transport code (where nuclear cross sections are used as inputs), it can be validated if the model prediction matches the measured counts. While critical benchmarks are the primary means for validation of criticality safety applications, there are some important parameters to which subcritical benchmarks are more sensitive and therefore superior validation tools. Subcritical benchmarks are also useful to the nuclear counterterrorism and non-destructive analysis (NDA) communities.

Figure 13: ISSA set up at B255 showing water tank and four He3 detectors

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[1] Nelson A.J., *et al*. "Fundamental physics subcritical neutron multiplicity benchmark experiments using water moderated highly enriched uranium fuel" (2019) https://www.osti.gov/servlets/purl/1566025

7.10 A.10 Photonuclear Reactions for Isotopic Signature Measurements (PRISM)

Development of new technologies for nuclear security applications requires advances in experimental nuclear physics, accelerator physics, detector development, and nuclear reaction modeling. Accordingly, LLNL's new linear accelerator — Photonuclear Reactions for Isotopic Signature Measurements (PRISM) — provides unique experimental capabilities. Coupled with a bremsstrahlung converter, PRISM operates as a high-energy, high-intensity photon source for a range of applications. In support of stockpile stewardship and national security missions, LLNL scientists can use the PRISM system to measure photo-nuclear cross sections and infer quantities of interest for a variety of nuclear materials. The system's flexibility for measurements at lower energies supports important physics research that addresses both programmatic and fundamental science needs.

General Description:

PRISM is an electron and photon source housed at LLNL's B194 Accelerator Facility and focused on nuclear physics and radiation effects research. Not a user facility but budgeted to maintain operations and beam time is available at the cost of operator's time.

Accelerator:

Normal-conducting S-band RF electron linac with thermionic source.

Beams:

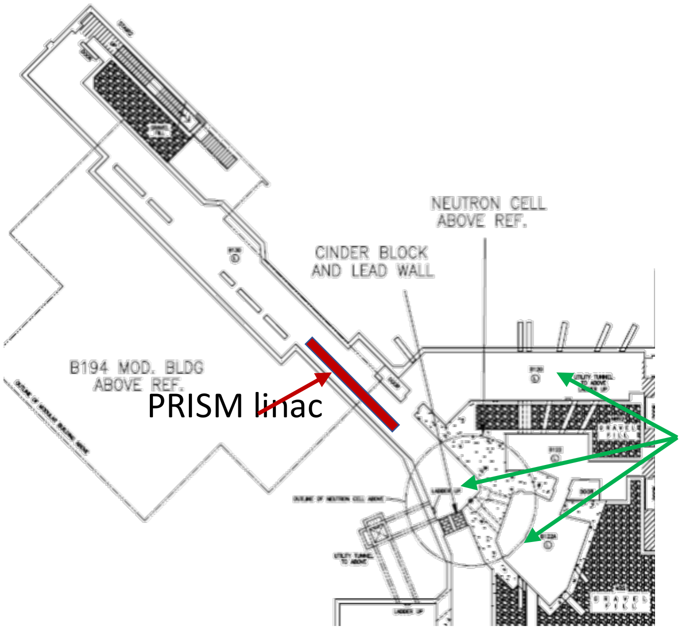
- 25 MeV, up to 30 μA electron beam; 1% energy spread
- Future upgrade to 50 MeV
- Bremsstrahlung converter for photon production; approximately 10^{14} γ/sec

Experimental focus:

Nuclear physics in support of stockpile stewardship and national security missions including photo-nuclear cross section measurements. Radiation effects research.

Detector arrays:
None/user provided.

Contact person: Scott Anderson, anderson131@llnl.gov, (925) 422-0195



Bremsstrahlung converter locations and experimental caves

Figure 2: The PRISM linac is installed in the B194 Accelerator Complex at LLNL and can send electron or photon beams into the shielded 0° Cave with line-of-sight ports into the adjacent Inner and Outer Detector Caves.

7.11 A.11: Los Alamos National Laboratory, Isotope Production Facility

General Description: Radionuclide Production for DOE Isotope Program housedin the LANSCE accelerator at Los Alamos National Laboratory; not a user facility but maintaining limited funding and staff for collaborative research

Beams: 40-100 MeV, 0.1 – 250 µA proton beams; Unmoderated 10^{13} cm^{-1} s^{-1} spallationneutron flux

Additional Capabilities: Hot cell facilities forremote manipulation of intense sources, radiochemical characterization and separations expertise, alpha/beta/gamma spectroscopy, 200-800 MeV protons at LANSCE-WNR

Research Focus: Isotope production, nuclear data for proton-induced reactions,radiochemical separations research.

Contact person: Eva Birnbaum; eva@lanl.gov; +1 505 665 7167

Prepared by Jonathan W Engle

The LANL Isotope Production Facility (IPF) is a dedicated target irradiation facility located at the Los Alamos Neutron Science Center (LANSCE), which accepts up to 100 MeV protons at beam currents upto 250 µA (and up to 450 µA in the future) to produce isotopes via LANL's 800-MeV accelerator. Three target slots allow target irradiation to be optimized by energy range for a particular isotope. Available beam time is estimated to be ~3000 hours / year.

The Los Alamos Hot Cell Radiological Facility is a cGMP compliant facility located at TA-48 consisting of 13 hot cells with a sample load shielding capacity of 1 kCi of 1 MeV gamma rays per cell for the remote handling of highly activated samples. The Hot Cells are equipped for separation, purification and wet chemistry activities with standard laboratory equipment, and the ability to perform radioassay of materials within the cells. The facility also contains fume hoods for radiological chemistry and reagent preparation. Available instrumentation includes counting capabilities described above, ICP-OES, HPLC, balances, centrifuges, and access to shared capabilities for materials diagnostics and characterization.

The LANL Count Room capability occupies more than 7000 square feet of LANL Building RC-1 at TA-48 and is dedicated to performing qualitative and quantitative assay of gamma, beta, and alpha-emitting radionuclides in a variety of matrices and over a wide range of activity levels. Founded in support of the US Testing Program, this facility is currently funded ~70% by a range of national security programs, and the balance in support of other internal and external customers. The Count-room's more than 65 systems include High Purity Germanium (HPGe) gamma- and X-ray spectrometers, alpha spectrometers and counters, and beta counters, operate 24x7x365, and perform more than 70,000 measurements annually.

7.12 A.12: Los Alamos National Laboratory, Los Alamos Neutron Science Center

General Description: US DOE NNSA National Laboratory, NNSA User Facilities, proton and neutron beams for basic and applied research in nuclear science, materials research, and fundamental science. Proposals submitted online are rated for scientific/applied merit by PAC. Proprietary proposals at Target 4 cost-recovery rates: $11k/1st day, $9k/day after 1st day.

Accelerator: Proton Linear Accelerator (100 MeV (IPF) and 211-800 MeV) dual H^+ and H^- beams.

Beams:

- *Neutrons*: Target 4 - bare tungsten neutron production target, 6 flight paths 8 to 90 m, proton $\Delta t < 1$ ns
- *Neutrons:* Target 1 flux-trap water & LH_2 moderated – 3+ flight paths, 8 to 20 m
- *Neutrons*: Target 4 East Port – neutron irradiations – moderated or un-moderated, 10^{11} n/cm^2-s @ 0.7 m
- *Neutrons*: Target 4 60R pre-collimator neutron irradiations – 10^9 n/cm^2-s @ 10 m
- *Protons*: Target 2 Blue Room – (low neutron return) 12 m dia. room, 211 – 800 MeV protons, 80 nA average, higher for LSDS or shielded target.
- *Protons*: Planned high current irradiations in Area A.

Experimental focus: neutron-induced nuclear reactions, fission studies, prompt reactions, activation and decay studies, isotope production cross sections, proton-induced nuclear reactions. Neutron imaging/CT Target 1 & Target 4, energy-selective imaging.

Proton flash radiography. Ultra-cold neutrons/fundamental physics.

Detector arrays: High-energy neutron PSD 54-detector array, Low-energy neutron 22-Li-glass array, fission time projection chamber, DANCE – 160 BaF2 array for (n,γ)

Contact person: LANSCE User Office; lansce-user-office@lanl.gov ; +1 505 665 1010

Prepared by Ron Nelson & Steve Wender

The Los Alamos Neutron Science Center (LANSCE) facilities for Nuclear Science consist of a high-energy "white" neutron source (Target 4) with 6 flight paths, three low-energy nuclear science flight paths at the Lujan Center (Target-1), and a proton reaction area (Target-2). The neutron beams produced at the WNR Target 4 complement those produced at the Lujan Center because they are of much higher energy and have shorter pulse widths. The 800 MeV proton beam of the LANSCE linear accelerator or linac drives the neutron sources. Proposals for beam time at the neutron production targets, Blue Room, and proton radiography facilities may be submitted for open research or proprietary work. See http://lansce.lanl.gov "Facilities" and "User Resources" tabs for details on the facilities and proposal submission.

Neutron beams with energies ranging from approximately 0.1 MeV to greater than 600 MeV are produced in Target-4. The Target-4 neutron production target is a bare unmoderated tungsten cylinder that is bombarded by the 800 MeV pulsed proton beam from the LANSCE linear accelerator and produces neutrons via spallation reactions. Because the proton beam is pulsed, the energy of the neutrons can be determined by time-of-flight (TOF) techniques. The time structure of the proton beam can be easily changed to optimize a particular experiment. Presently, Target-4 operates with a proton beam current of approximately 4 μA, 1.8 μs between pulses and approximately 35,000 pulses/sec. Target-4 is the most intense high-energy neutron source in the world and has 6 flight paths instrumented for a variety of measurements.

In the Target-2 area (Blue Room), samples can be exposed to the 800 MeV proton beam directly from the linac, or with more peak intensity with a beam that has been accumulated in the Proton Storage Ring (PSR). Although the total beam current is limited by the shielding in Target-2, the PSR beam provides significantly greater peak intensity than the direct beam from the accelerator. Target-2 is used for proton irradiations and hosts the Lead Slowing-Down Spectrometer (LSDS). Proton beams with energies as low as 211 MeV can be transported to Target-2.
At present there are three flight paths at the Lujan Center that are devoted to Nuclear Science research. Other flight paths are devoted to Materials Science research. These flight paths view a moderated target with both water and liquid hydrogen moderators and have useful neutron fluxes that range from sub-thermal to approximately 500 keV.

With these facilities, LANSCE is able to deliver neutrons with energies ranging from a meV to several hundreds of MeV, as well as proton beams with a wide range of energy, time and intensity characteristics. The facilities, instruments and research programs are described briefly below.

7.12.1 Overview of the Flight Paths

Each Flight Path name identifies the target and the direction of the flight path (FP) with respect to the proton beam. For example, 4FP15R is a FP (flight path) that starts at Target 4 and is 15 degrees to the right (15R) of the incoming proton beam. Figure 18 shows the layout of the flight paths.
The neutron fluxes available are shown in Figure 19.

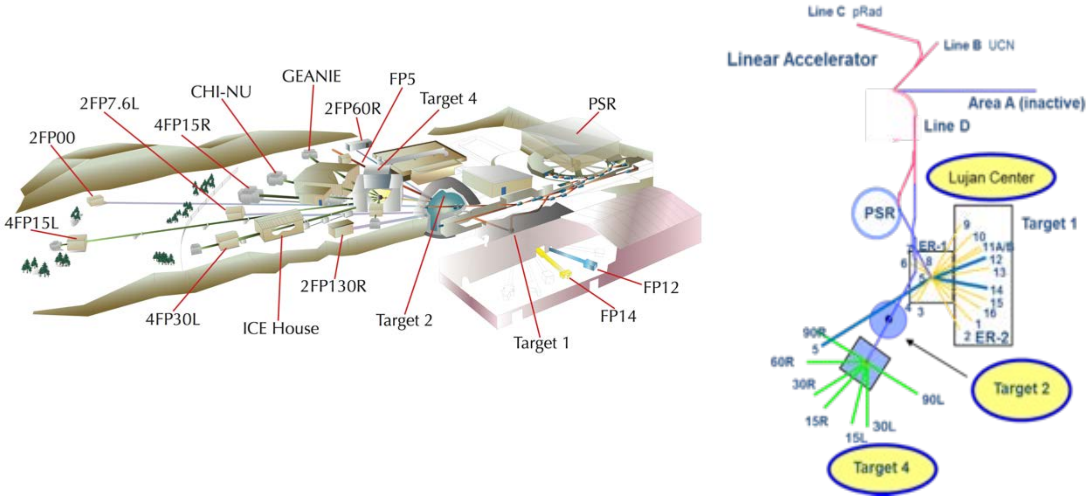


Figure 18. Two different views of the layout of the Target-1, 2, and 4 flight paths at the LANSCE neutron sources.

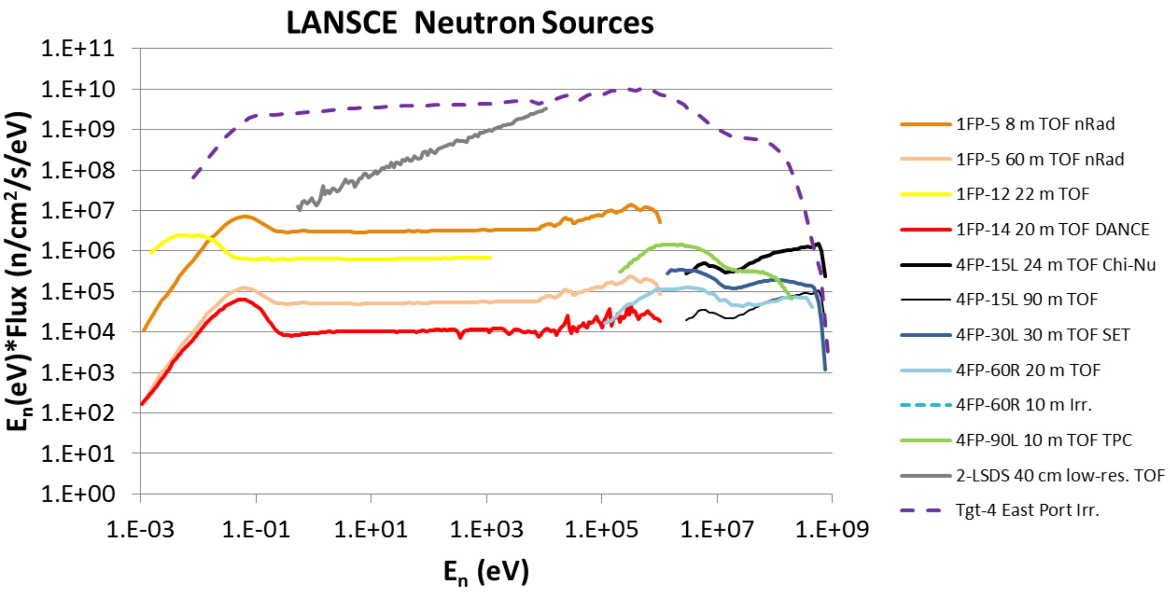


Figure 19. Graphs of the neutron flux times energy (also known as the flux/unit lethargy) for a representative sample of the neutron time-of-flight (TOF) and irradiation (Irr.) stations at LANSCE. The data are from measurements or calculations vetted against measurements

7.12.2 Target 4 Flight Paths (FP)

For the Target-4 flight paths, the neutron spectrum depends on the angle of the flight path with respect to the proton beam with the higher-energy neutron flux greater at the more forward angles. Below we list the main activities that are presently being performed on each flight path.

- **4FP90L** is the location of the Time-Projection Chamber (TPC) that is used to measure fission cross sections to high precision.
- **4FP30L** The ICE House is ~20 m from the production target and is used by industry, universities, and national laboratories for semiconductor electronics testing (SET) to measure neutron-induced failures in devices.
- **4FP15L** has two experimental locations available at distances of 22 and 90 meters from the spallation target. Primarily used for the Chi-Nu experiments at 22 meters. Chi-Nu is measuring the fission neutron output spectrum. A low-neutron-return room is below the 22 m station. The 90 m flight path is used mostly for neutron detector development and calibration
- **4FP15R** is a general purpose flight path that is now being used for neutron radiography, the SPIDER detector (fission product yields) and the low-energy (n,z) (LENZ) experiment.
- **Industry, universities, and national laboratories primarily use 4FP30R or ICE II station at 15 m** for SET.
- **4FP60R** The 20 m station is used for gamma-ray spectroscopy and other experiments. An irradiation station using peripheral beam is available at 10 m.

7.12.3 Target 2 (Blue Room)

- Target 2 is used for proton beam irradiation experiments. Beam is available directly from the linac or from the proton storage ring (PSR). Present and past experiments include:
- A lead slowing-down spectrometer (LSDS) provides very large effective neutron fluxes in the energy range from ~1 eV to ~10 keV with low neutron energy resolution for measuring cross sections with ultra-small samples.
- Pulsed beam experiments to simulate intense neutron environments for semiconductor certification.
- Proton irradiation of detectors and radiation-hardness testing of components for the Large Hadron Collider at CERN.
- Measurement of radioisotope production cross sections for the Isotope Production Facility (IPF) at LANSCE (see the IPF contribution to this report).

7.12.4 Target 1 Lujan Center Flight Paths

- **FP5** is a water-moderated general purpose flight path that is currently being used for neutron radiography. It has two detector areas: one at approximately 10m in ER-1 and the second at a distance of 60 m that is reached from the Target-4 yard. The 60 m station has a large field of view.
- **FP14** is the location of the Detector for Advanced Neutron Capture Experiments (DANCE). It consists of a 4-π array of BaF_2 scintillators designed for neutron capture measurements on sub-milligram and radioactive samples. These measurements support radiochemical detector cross section measurements for Defense Programs, and experiments for nuclear astrophysics.
- **FP12** is a cold-moderator flight path currently used by the SPIDER spectrometer to measure fission fragment yields. FP12 has a neutron guide.

7.12.5 Other Experimental Areas

Target-4 East Port provides a mechanism for irradiating samples in the intense broad spectrum neutron field at 0.7 m from the Target-4 neutron production target. Samples can be moved from the irradiation position to a storage position by remote control.

Proton Radiography Facility The pRad facility provides fast imaging of static and dynamic systems. See http://lansce.lanl.gov/pRad/index.shtml for more information.

Ultra-Cold Neutron (UCN) Facility State-of-the-art UCN Facility See http://lansce.lanl.gov/UCN/index.shtml

7.13 A.13 Criticality Experiments Research Center (NCERC)

General Description: US DOE NNSA facility located at the Nevada National Security Site (NNSS), operated by Los Alamos National Laboratory (LANL). Not a user facility but some ability to support collaborative research.

Critical Assembly Machines:

Planet: General-purpose, light-duty, vertical lift critical assembly machine comprised of an upper stationary platform and a lower movable platen. Load limit 2,000 lbs on the stationary platform and 1,000 lbs on the platen

Comet: General-purpose, heavy-duty vertical lift critical assembly machine consisting of an upper stationary platform and a lower moveable platen. Load limit of 20,000 lbs on the stationary platform and 2,000 lbs on the platen.

Flattop: One-dimensional geometry, fast benchmark critical assembly. Spherical fissile core surrounded by a 1000 kg spherical natural uranium (NU) reflector. Two available cores: highly enriched uranium (HEU) metal (93 weight percent U-235) and δ-phase plutonium metal (4.8 atom percent Pu -240).

Godiva IV: Fast burst critical assembly, approximately 65 kg of HEU fuel alloyed with 1.5 percent molybdenum, nominally six inches tall and seven inches in diameter. Bursts up to $1.15 above delayed critical.

Subcritical Radiation Test Objects: Subcritical configurations of Special Nuclear Material (SNM) vary in SNM type, mass, form, and geometry, resulting in a wide range of subcritical neutron multiplication (from near 1 to about 20).

Experimental focus: Performing experiments in the subcritical, critical, super-critical, and super-prompt critical regimes for training, radiation measurements, and to provide information for the criticality safety community.

Detector systems:

Neutron Noise Measurements: NoMAD, sets of He-3 detectors, plastic/liquid scintillators. Used to examine Rossi-α, Feynman Variance-to-Mean, and pulsed neutron source measurements.

Count Room: HPGe detectors to measure activation/fission foils, automatic sample changer, 8 channel alpha spectrometer, rabbit system in progress.

Radiation Generating Devices: XRS X-ray generators, D-T neutron generators, and a 6 MeV Betatron.

Contact person: Joetta Goda, jgoda@lanl.gov

Prepared by Joetta Goda & Geordie McKenzie

NCERC is a general-purpose criticality experiments facility located inside the Device Assembly Facility (DAF) at the Nevada National Security Site (NNSS). From 1967-2006, the Los Alamos Critical Experiment Facility (LACEF) team conducted experiments at Los Alamos National Laboratory's Technical Area 18 (TA-18). In 2006, operations ceased and LACEF began the process of relocating operations to the Nevada National Security Site (NNSS).

NCERC can perform experiments in the subcritical, critical, super-critical, and super-prompt critical regimes. Experiments conducted at NCERC can utilize an inventory of unique nuclear material items, including HEU and WGPu items in various material forms, (metal, oxide, etc...) that are highly configurable. These items can be configured with a wide array of interstitial and/or reflector materials.

7.13.1 Available Experimental Assemblies

The experimental capabilities at NCERC include subcritical experiments and four critical assembly machines. The four critical assembly machines are Comet, Planet, Flattop, and Godiva IV. Subcritical configurations of Special Nuclear Material (SNM) are built by hand. The configurations vary in SNM type, mass, form, and geometry, resulting in a wide range of subcritical neutron multiplication (from near 1 to about 20). These configurations often include moderator and/or reflector materials, and are primarily used for training, radiation measurements, detector testing, and to provide information for the criticality safety community.

The Planet vertical assembly machine is a light-duty, general-purpose, vertical lift critical assembly machine comprised of an upper stationary platform and a lower movable platen [1]. The primary purpose of Planet is to conduct critical experiments, by remotely bringing together two halves of a critical assembly into a critical configuration. Gravity is used to provide a shutdown mechanism. The simple, yet effective, vertical lift allows for a wide variety of potential designs and can meet varied experimental needs. Critical experiments are used to determine critical masses of fissile and fissionable material (uranium, plutonium, neptunium, etc.). Planet can accommodate a load of 2,000 lbs on the stationary platform and 1,000 lbs on the movable platen. The Planet critical assembly is limited to an excess reactivity of 80 cents.

Comet is a general-purpose, heavy-duty vertical-lift critical assembly machine used to conduct critical and subcritical experiments, nuclear safety studies, and criticality safety training [2]. The machine consists of a movable platen and an upper, stationary platform. Operations are performed by installing two subcritical configurations made up of fissile material, interstitial materials and/or reflectors on both platforms. Reactivity can be added by raising the moveable platen and decreasing the distance between the two portions of the system, or by inserting fissile material into a reflector. Comet can accommodate loadings of up to 20,000 lbs on the stationary platform and 2,000 lbs on the lower platen. The Comet assembly is limited to an excess reactivity of 80 cents.

Flattop is a simple, one-dimensional geometry, fast benchmark critical assembly, consisting of a spherical fissile core surrounded by a 1000 kg spherical natural uranium (NU) reflector [3]. The two available cores of special nuclear material (SNM) are highly enriched uranium (HEU) metal (uranium 93% U-235 by weight percent) and δ-phase plutonium metal (plutonium 4.8% Pu-240 by atom percent). The reflector consists of two movable quarter-spheres and a stationary hemisphere. Originally assembled in the late 1950s, Flattop was used to develop and to validate nuclear data and simple one-dimensional, two-region computational models. A half-inch glory hole extends through the core and stationary reflector. Materials can be inserted into the glory hole for replacement measurements or irradiations. The Flattop critical assembly is limited to an excess reactivity of 80 cents when using the uranium core and 50 cents when using the plutonium core.

Godiva IV is a fast burst critical assembly constructed of approximately 65 kg of HEU fuel alloyed with 1.5 percent molybdenum for strength [4]. The cylindrical core is nominally six inches tall and seven inches in diameter. Godiva IV was designed and built in 1967, following several earlier incarnations of uranium burst assemblies. Godiva is one of the last such critical assemblies in the United States and can be used for studies of super-prompt critical behaviour as well as irradiations and demonstrations. Godiva is limited to performance of bursts with less than $1.15 of excess reactivity.

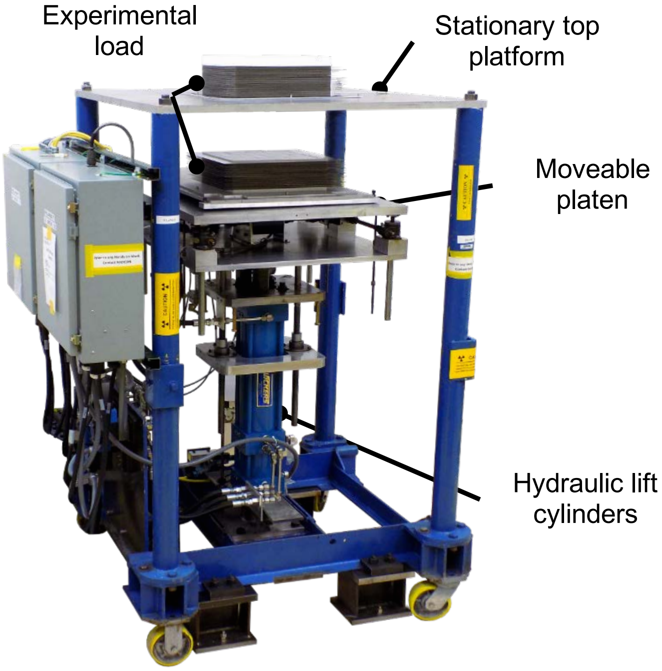


Figure 1. Planet Critical Assembly

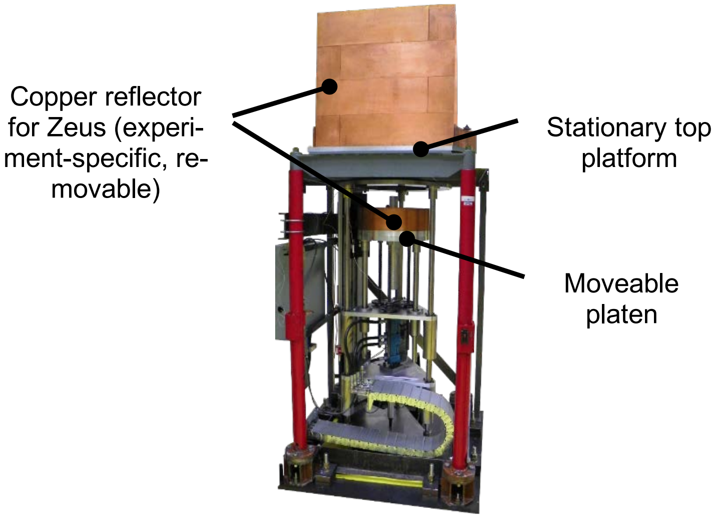


Figure 2. Comet Critical Assembly

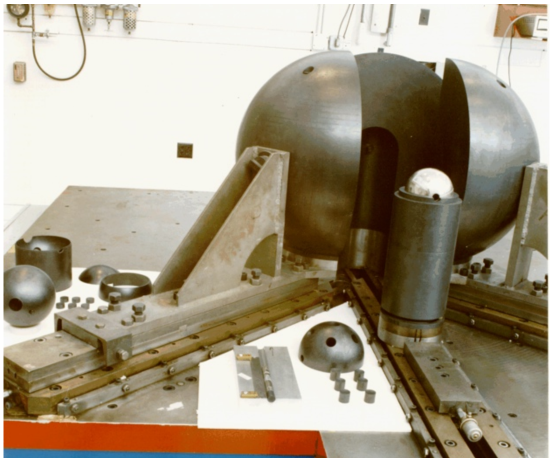


Figure 3. Flattop Critical Assembly

Figure 4. Godiva IV Critical Assembly

7.13.2 Fuel and material available

NCERC maintains an inventory of a wide array of uranium and plutonium metal fuels in many geometric forms such as plates, discs, hemi-shells [5]. There is some limited inventory of other material forms such as oxides, carbides, hydrides, etc. Additionally, NCERC maintains reflector/moderator materials such as beryllium, tungsten, tantalum, molybdenum, polyethylene, copper, etc. This list is not exhaustive, and practically any material can be used in criticality studies at NCERC. Criticality safety evaluations allow the assembly of fissionable material and other materials into approved configurations to be used as Radiation Test Objects and Inspection Objects.

7.13.3 Capabilities for additional measurements/unique capabilities

NCERC is home to several additional capabilities including neutron noise measurement systems, a count room to measure activation/fission foils, and radiation generating devices. The neutron noise measurement systems which include both He-3 tubes and plastic/liquid scintillators can examine Rossi-α, Feynman Variance-to-Mean, and pulsed neutron source measurements. The count room includes well characterized HPGE detectors and an 8-channel alpha spectrometer. One of the HPGE systems is mounted on a computerized sample changer capable of automatically switching between several samples. NCERC maintains and operates multiple radiation generating devices including XRS X-ray generators, D-T neutron generators, and a 6 MeV Betatron.

7.13.4 References

[1] Rene Sanchez, Theresa Cutler, Joetta Goda, Travis Grove, David Hayes, Jesson Hutchinson, George McKenzie, Alexander McSpaden, William Myers, Roberto Rico, Jessie Walker & Robert

Weldon (2021) A New Era of Nuclear Criticality Experiments: The First 10 Years of Planet Operations at NCERC, Nuclear Science and Engineering, 195:sup1, S1-S16, DOI: 10.1080/00295639.2021.1951077

[2] Nicholas Thompson, Rene Sanchez, Joetta Goda, Kelsey Amundson, Theresa Cutler, Travis Grove, David Hayes, Jesson Hutchinson, Cole Kostelac, George McKenzie, Alexander McSpaden, William Myers & Jessie Walker (2021) A New Era of Nuclear Criticality Experiments: The First 10 Years of Comet Operations at NCERC, Nuclear Science and Engineering, 195:sup1, S17-S36, DOI: 10.1080/00295639.2021.1947105

[3] David Hayes, Todd Bredeweg, Theresa Cutler, Joetta Goda, Travis Grove, Jesson Hutchinson, Juliann Lamproe, George McKenzie, Alexander McSpaden, William Myers, Rene Sanchez & Jessie Walker (2021) A New Era of Nuclear Criticality Experiments: The First 10 Years of Flattop Operations at NCERC, Nuclear Science and Engineering, 195:sup1, S37-S54, DOI: 10.1080/00295639.2021.1947104

[4] Joetta Goda, Caiser Bravo, Theresa Cutler, Travis Grove, David Hayes, Jesson Hutchinson, George McKenzie, Alexander McSpaden, William Myers, Rene Sanchez & Jessie Walker (2021) A New Era of Nuclear Criticality Experiments: The First 10 Years of Godiva IV Operations at NCERC, Nuclear Science and Engineering, 195:sup1, S55-S79, DOI: 10.1080/00295639.2021.1947103

[5] Jesson Hutchinson, John Bounds, Theresa Cutler, Derek Dinwiddie, Joetta Goda, Travis Grove, David Hayes, George McKenzie, Alexander McSpaden, James Miller, William Myers, Ernesto Andres Ordonez Ferrer, Rene Sanchez, Travis Smith, Katrina Stults, Nicholas Thompson & Jessie Walker (2021) A New Era of Nuclear Criticality Experiments: The First 10 Years of Radiation Test Object Operations at NCERC, Nuclear Science and Engineering, 195:sup1, S80-S98, DOI: 10.1080/00295639.2021.1918938

7.14 Appendix A.14: Facility for Rare Isotope Beams

General Description: University-based, national user facility focused on basic research in low-energy nuclear science, accelerator science, fundamental symmetries and societal applications.

Accelerators: a linear accelerator driver up to 200 MeV/u, one re-accelerator up to 6 MeV/u

Beams: Over 1000 rare isotopes produced both neutron-rich and neutron deficient.

Beam rates are available from:
https://groups.nscl.msu.edu/frib/rates/fribrates.html
Beam time is allocated by PAC.

Website: https://frib.msu.edu

Experimental focus (relevant to applications):

- Beams of most isotopes of data interest
- Decay spectroscopy
- Neutron capture rate inference on short-lived rare isotopes
- Isotope Harvesting

Present detector array capabilities (relevant to applications):

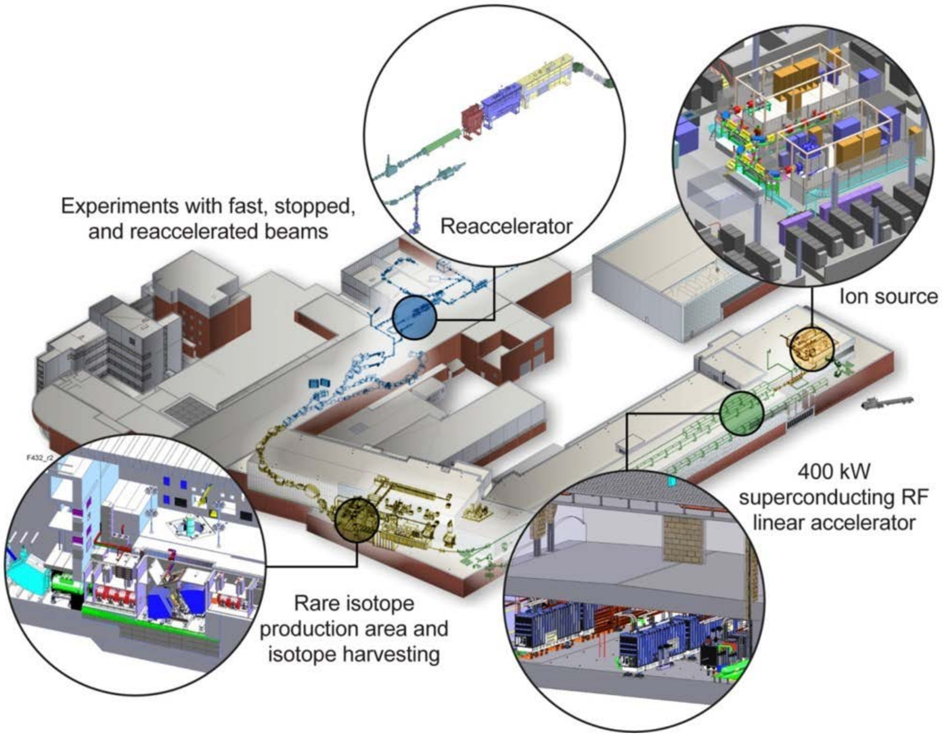
- Decay spectroscopy station
- Total absorption gamma-ray spectrometers (SuN, MTAS)
- Proof-of-principle isotope harvesting station

Contact person: Sean Liddick

Facility provides unique access to rare isotopes over a broad energy range including thermal, few MeV/nucleon to ~200 MeV/nucleon. It includes a large complement of state-of-the art experimental equipment for study of nuclear properties and reactions.

7.14.1 Decay Spectroscopy

Motivation: Decay spectroscopy provides a number of quantities of interest for the low-energy nuclear science community such has half-lives, delayed neutron-branching ratios, and delayed gamma-ray transitions. Absolute gamma-ray intensities can be obtained based on ion-by-ion counting of the radioactive ion beam and the beta-delayed gamma rays are used to elucidate the low-energy level scheme of the daughter nucleus. High- and low-resolution delayed gamma-ray studies can be used to infer average electron and gamma-ray energies emitted following beta decay.



General layout of experimental equipment at the FRIB See https://frib.msu.edu for more detail.

Detection System: The detection system consists of either a central Si or Ge detector for ion and beta-decay electron detection [1,2]. Multiple ancillary arrays existed for delayed emissions including gamma-rays and neutrons [3,4,5,6].

Recent Results: Conversion electron emission from an isomer state was monitored in ^{68}Ni to extract E0 monopole transition strengths [7]. Decays of various neutron-rich isotopes were studied to determine low-energy level schemes and identify gamma and beta-emitting isomeric states [8]. Total absorption spectroscopy addressed deficiencies in previously reported decay scheme of ^{76}Ga into ^{76}Ge.

7.14.2 References

1. "*Beta counting system for fast fragment beams*", J. I. Prisciandaro *et al.*, Nucl. Instrum. Meth. Phys. Res. A **505**, 140 (2002).
2. "*High Efficiency Beta-decay Spectroscopy using a Planar Germanium Double-Sided Strip Detector*", N. Larson *et al.*, Nucl. Instrum. Methods in Phys. Res. A, **727**, 59 (2013).
3. "*Thirty-two-fold segmented germanium detectors to identify gamma rays from intermediate-energy exotic beams*", W.F. Mueller *et al.*, Nucl. Instrum. Meth. in Phys. Res. A, **466**, 492 (2001).
4. "*The neutron long counter NERO for studies of beta-delayed neutron emission in the r-process*", J. Pereira *et al.*, Nucl. Instrum. Meth. in Phys. Res. A, **618**, 275 (2010).
5. "*Half-lives and branchings for beta-delayed neutron emission for neutron-rich Co-Cu isotopes in the r-process*", P. Hosmer *et al.*, Phys. Rev. C, **82**, 025806 (2010).
6. "*SuN: Summing NaI gamma-ray detector for capture reaction measurements*", A. Simon *et al.*, Nucl. Instrum. Meth. in Phys. Rev. A, **703**, 16 (2013).
7. "*Shape coexistence in Ni-68*", S. Suchyta *et al.*, Phys. Rev. C **89**, 021301 (2014).
8. "*Low-energy level schemes of* ^{66,68}*Fe and inferred proton and neutron excitations across Z = 28 and N = 40*", S. Suchyta *et al.*, Phys. Rev. C, **87**, 014325 (2013).

7.14.3 Neutron Capture Rates of Short-Lived Rare Isotopes

Motivation: Neutron capture rates impact a wide variety of fields including nuclear astrophysics, national security, and nuclear power generation. The need for neutron capture rates on short-lived nuclei has motivated a number of indirect techniques. At NSCL, a new technique has been developed to infer neutron capture rates by determining the basic nuclear properties of radioactive ions.

Technique: The detection system consists of a small beta-decay-electron sensitive detector inserted into a large total absorption gamma-ray spectrometer called the Summing NaI detector (SuN) [1] at NSCL. Radioactive ions are produced and delivered to SuN and the resulting beta-delayed gamma rays are detected. Gamma-ray emission from highly excited states in the daughter nucleus is used to extract the functional form of the gamma-ray strength and nuclear level density. These quantities are inserted into Hauser-Feshbach calculations to infer neutron capture rates.

Recent Results: The technique has been applied to the neutron capture of ^{75}Ge, which is unstable ($t_{1/2}$ = 83 min), see Figure 21 [2]. Further work is anticipated in neutron-rich Fe and Sr regions for nuclear astrophysics and national security applications.

7.14.4 References

1. "*SuN: Summing NaI gamma-ray detector for capture reaction measurements*", A. Simon *et al.*, Nuclear Instrum. Methods in Phys. Rev. A, **703**, 16 (2013)
2. "*Novel Technique for constraining r-process (n,□□ reaction rates*", A. Spyrou *et. al.*, Phys. Rev. Lett. **113**, 232502 (2014).

7.14.5 Isotope Harvesting

Motivation: The vast majority of rare isotope beams used in experiments at the NSCL and that will be produced at FRIB only live for a few seconds or less. However, a very large number of longer-lived isotopes that have important uses in medical research (and other applications) are not collected during normal operations. The long-term possibilities for isotope harvesting have been assessed in an ongoing series of user workshops. A collaboration of researchers at Hope College and Washington University in St. Louis are working with NSCL researchers to develop systems and to solve problems associated with harvesting the unused isotopes at now at the NSCL, and eventually FRIB, for off-line experiments.

Detection System: The team from Hope College designed and built an end-station to fill, irradiate and collect samples of 100 milliliters of water. The collection system does not have any metal parts in contact with the water so that only metallic elements delivered by the beam will remain in the water. The group from Washington University in St. Louis developed chemical processing schemes to purify the various elements, removing all the unwanted activities that might be present, and to chemically attach the collected radioisotopes to biological molecules for testing. The next step in this work is the construction of a new system to collect long-lived isotopes from the cooling water in the NSCL A1900 beam blocker. The beam blocker is at the exit of the first large bending magnet of the fragment separator and is often used to intercept the unused primary beam.

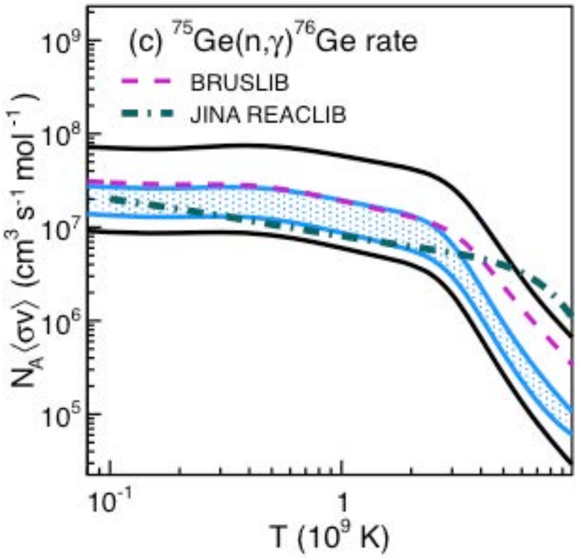


Figure 21. Maxwellian-averaged reaction rate as a function of stellar temperature compared to rates from BRUSLIB and JINA REACLIB and TALYS limits.

Recent Results: The first experiments produced and extracted the relatively easy isotope ^{24}Na. Subsequently ^{67}Cu was extracted from a relatively pure sample and then this isotope was extracted from a very contaminated sample similar to what would be present in the NSCL and FRIB beam dumps. The ^{67}Cu was used to create a radioactive antibody that was injected into mice and the distribution of the activity in different biological materials was determined.

7.14.5.1 References

1. Design and construction of a water target system for harvesting radioisotopes at the National Superconducting Cyclotron Laboratory, A. Pen, *et al*., Nucl. Instrum. Meth. A 747**,** 62 (2014).
2. Feasibility of Isotope Harvesting at a Projectile Fragmentation Facility: ^{67}Cu, T. Mastren, *et al*., Nature/Scientific Research **4,** 6706 (2014).

7.15 A.15 University of Missouri, MURR Research Reactor

General Description: Multi-disciplinary, university-based research and educationalreactor and cyclotron facility
Beams: Thermal-fast (fission) neutrons peakflux @6.5x10^{14} n/cm^{2}s, 16MeV protons Reactor power: 10MW(thermal)
Additional Capabilities: Neutron source-fieldirradiation, gamma-ray spectroscopy
Research Focus: Medical/industrial/researchisotope production (DoE funded, Private industry funded), neutron scattering, metrology (elemental analysis, (NAA)
Contact person: David Robertson, Les Foyto(see below)

Prepared by Nickie Peters

The University of Missouri Research Reactor (MURR) is a multi-disciplinary research and educational facility providing a broad range of analytical, materials science and irradiation services to the research community and the commercial sector. Scientific programs include research in archaeometry, epidemiology, health physics, human and animal nutrition, nuclear medicine, radiation effects, radioisotope studies, radiotherapy, boron neutron capture therapy and nuclear engineering; and research techniques including neutron activation analysis, neutron and gamma-ray scattering and neutron interferometry. The MURR is situated on a 7.5-acre lot in the central portion of the University Research Commons, an 84-acre tract of land approximately one mile (1.6 km) southwest of the University of Missouri at Columbia's main campus (see Figure 1). The heart of this facility is a pressurized, reflected, open pool-type, light water moderated and cooled, heterogeneous reactor designed for operation at a maximum steady-state power level of 10 Megawatts thermal Operates 24 hours a day, seven daysa week, 52 weeks a year

7.15.1 General Information

- 10 MW research reactor
- Operates 24 hours a day, seven days a week, 52 weeks a year
  - Uniquely operates on 52 weeks per year at full power
- Peak neutron flux: 6.5 x 10^{14} n/cm^{2}s
- 16 MeV cyclotron and laboratories

The MURR has six types of experimental facilities designed to provide these services: the Center-Test Hole (Flux Trap); the Pneumatic Tube System; the Graphite Reflector Region; the Bulk Pool Area; and the (six) Beamports.

Figure 1. General layout of the MURR facilities

The first four types provide areas for the placement of sample holders or carriers in different regions of the reactor core assembly for the purpose of material irradiation. Figure 2 shows the peak thermal (top panel), resonance (middle panel), and fast (bottom panel) flux distributions for the MURR core experimental facilities, revealing only two of the six Beamports. The peak of the thermal-neutron flux distribution is located in the central flux-trap of 4.42 x 10^{14} n·cm^{-2}s. The peak resonance-energy neutron flux is located broadly over the central core region of 2.17 x 10^{14} n·cm^{-2}s. The fast neutron flux distribution peaks at 3.11 x 10^{14} n·cm^{-2}s in the fuel assembly. Some of the material irradiation services include isotope production for the development of radiopharmaceuticals and life-science research. There is a filtered thermal neutron beam at MURR that has a maximum diameter of 6", a Cd ratio of >130, and a thermal neutron flux of 8.4x10^8 n/cm^2/s. The beam can be used for material studies, nuclear data measurements, and radiation hardness testing of electronics.

The Six beamports channel neutrons to experimental equipment that are utilized for material science research see Fig. 24. In particular, two of the four neutron scattering instruments: a triple-axis spectrometer (TRIAX) and a high-resolution powder diffractometer (PSD). TRIAX is a fully function thermal beam profile triple-axis spectrometer. It is capable of both elastic and inelastic spectroscopy to study chemical or magnetic structures or excitations such as phonons, spin-waves, and crystal field splitting. The PSD instrument has recently undergone a comprehensive upgrade in which the detector bank was expanded from 5 to 15 linear position-sensitive detectors. The electronic readout and computer interface were modernized while maintaining the original design that implements a double-focusing Si monochromator coupled with linear position-sensitive detectors to optimize diffraction counting at a steady-state source.

Table 1 shows the list of nuclides with applications in medicine and material science industrial that were produced atMURR in 2021 Many of these importantnuclides are lacking in their current nuclear data files, which hinder their production optimization. Each and every week MURR supplies the active ingredients for FDA-approved Quadramet,® TheraSpheres®; Ceretec™ (with Tc-99m), Lutathera,® and I-131.Specifically, MURR isotope production research activities includes: Carrier free lanthanides indirect production (Lu-177 and Tb-161) – a DOE Advanced Nuclear Medicine Initiative and Electromagnetic isotope separation (Sm-153); Mo-99 (n, gamma) production for novel Tc-99m generator technologies; Complementary set of proton-rich isotopes for area medical facilities and researchers, such as F-18(FDG) for PET scans and F-18 for clinical trials of new imaging agents, and Cu-64 for radiopharmaceutical research are produced in the 16 MeV cyclotron laboratories.

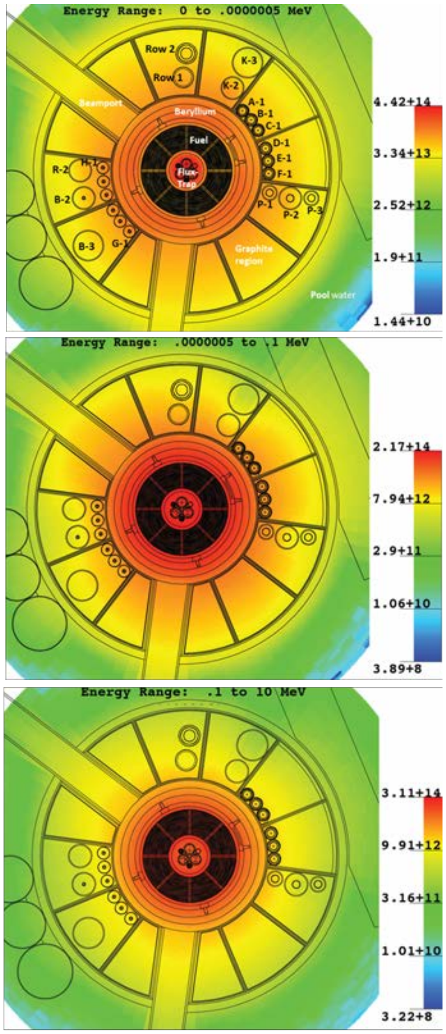
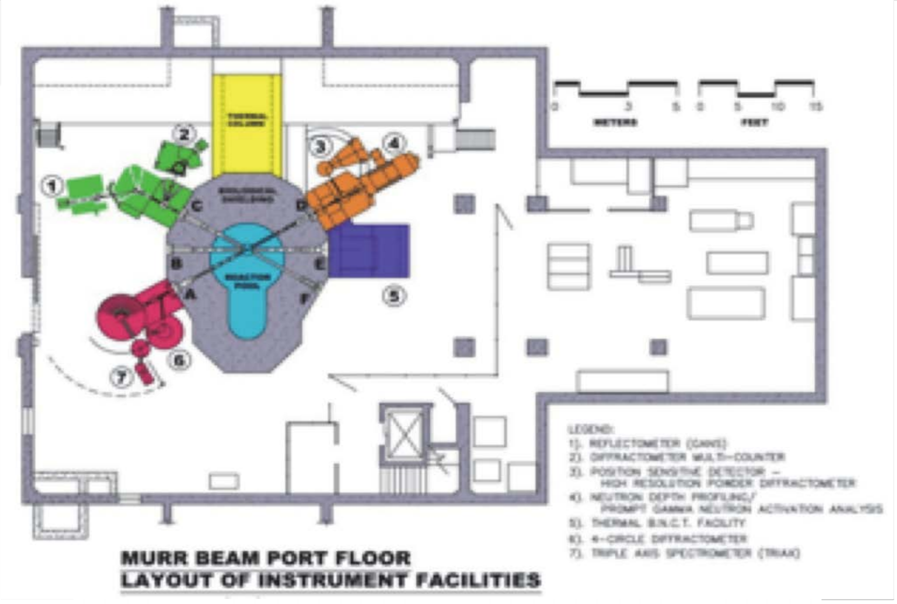


Figure 2: The peak thermal (top) resonance (middle) and fast (bottom) neutron flux distribution for the MURR core experimental locations

Table 1. Nuclides Produced at MURR in 2021

Isotope Production in 2021			
Ir-192	Eu-154	Se-75	Cr-51
Y-90	Eu-155	Sn-113	Fe-59
Ce-137	Hg-197	Te-121	P-32
Ce-137m	Hg-197m	Zr-95	Sr-85
Ce-139	Hg-203	Lu-177	Yb-169
Ce-141	I-131	Os-191	Sb-124
Ce-143	Nb-95	W-181	Sc-46
Pr-143	Nb-97	Sm-153	Kr-79
Co-60	Nb-97m	Po-210	Mo-99
Eu-152	Sb-122	Ca-45	Re-186



MURR BEAM PORT FLOOR
LAYOUT OF INSTRUMENT FACILITIES

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7.16 A.16: Notre Dame University, Nuclear Science Laboratory

General Description: University basedaccelerator laboratory

Accelerators:

- 10 MV Tandem Pelletron
- 5 MV 5U single ended Pelletron
- 3 MV 9S Tandem Pelletron
- 1 MV Pelletron at SURF
- TriSol radioactive beam device

Beams: *Protons, alphas, and heavy ions. Light radioactive ions A<40 can be produced by the TriSol facility*: Beams can be produced over a wide energy range at the FNtandem with terminal voltage up to 10MV. The typical beam intensities are in the μAmp range for protons and alpha particles, but lower for heavy ions. The 5U accelerator is equipped with a Nanogan ECR source capable of production of beams in higher ionization states. Typical beam intensities range in the ten to hundred μAmps. The 9S produces <10 MeV proton and alpha beams but is limited to a100-200 nA because of shielding. The SURF accelerator produces 200 μA proton and α beams.

Experimental focus: low energy nuclear reaction studies for nuclear astrophysics, radioactive beam physics with applications to astrophysics and fundamental symmetries, nuclear structure physics, PIXE and PIGE material analysis, nuclear reaction studies for isotope production, activation and decay studies for nuclear astrophysics with application potential. AMS with long-lived radioisotopes up to Uranium.

Present detector array capabilities (relevant to applications): AMS capability, Ge-gamma and 3He neutron detector arrays,Silicon particle detector array, St. George recoil separator, summing detectors, Enge spectrograph under construction.

Prepared by Dan Bardayan

The Nuclear Science Laboratory at Notre Dame is a university based accelerator lab whose main research focus is on nuclear astrophysics, radioactive beam physics and nuclear physics applications. The operation is funded through the National Science Foundation. The facility is not funded as a user facility but welcomes users. There is no specific PAC process, but collaboration with the NSL faculty isrecommended to facilitate user support. Presently 40% of the experiments are user based efforts.

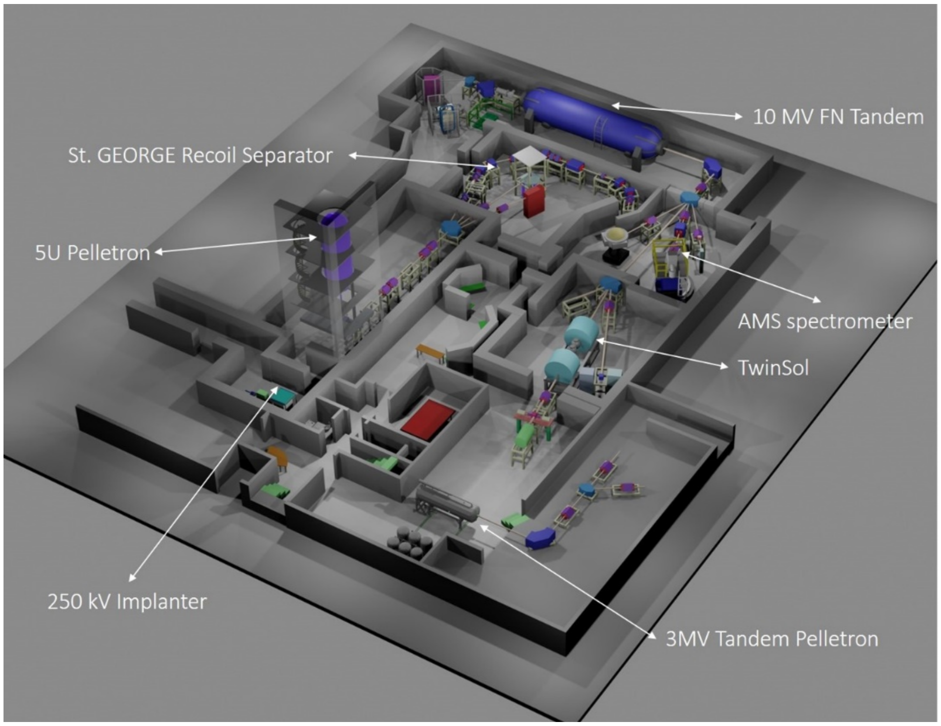
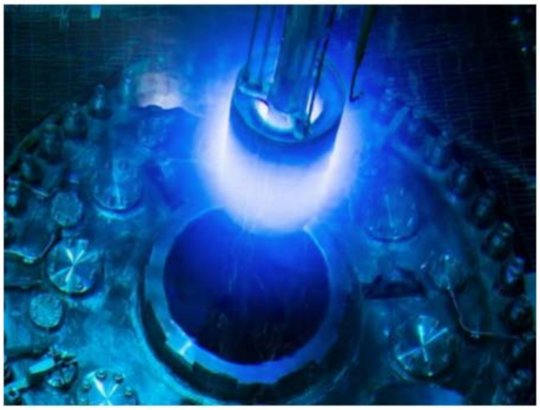
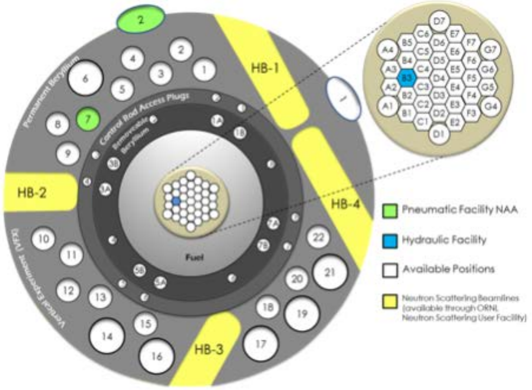


Figure 25. General layout of Notre Dame Nuclear Science Laboratory

The NSL operates a broad program in nuclear astrophysics, AMS physics and nuclear structure physics. The laboratory operates an FN Pelletron tandem accelerator and a high intensity 5MV single ended accelerator. Additionally a 3 MV Pelletron tandem has been installed dedicated for nuclear application studies. Applications are presently focused on AMS techniques as well as on PIXE and XRF based material science applications. A fourth acceleration is operated underground at the SURF facility. In terms of nuclear data the laboratory focuses primarily on nuclear astrophysics data such as low energy nuclear cross section measurements for stellar hydrogen, helium and carbon burning. This is complemented by nuclear reaction studies for determining nuclear reaction rates for explosive hydrogen burning environments.

7.17 A.17: Oak Ridge National Laboratory, High Flux Isotope Reactor (HFIR)





General Description:
85MW Research Reactor with very high neutron flux. Primary missions of

1. Neutron Scattering
2. Isotope Production
3. Materials Research
4. Nuclear Forensics

Beams:

- 4 Primary beamlines. (3 thermal and one cold).
- 12 Active instruments and 3 development instruments

Additional Capabilities:

- Isotope production/research
- Materials damage testing (neutron and gamma)
- Nuclear forensics via neutron activation analysis

Contact persons:
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Laura Edwards Morris (865.574.2966)
Neutron Activation Analysis:
David Glasgow (865.574.4918)
Gamma Irradiations:
Geoff Deichert (865.241.3946)

Prepared by Chris Bryan

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory is one of the world's most powerful nuclear research reactor facilities. It is a versatile 85-MW isotope production and test reactor with the capability and facilities for performing a wide variety of irradiation experiments.

The neutron scattering research facilities at HFIR contain a world-class collection of instruments used for fundamental and applied research on the structure and dynamics of matter. HFIR is also used for medical, industrial, and research isotope production; research on neutron damage to materials; and neutron activation analysis to examine trace elements in the environment.

Additionally, the building houses a gamma irradiation facility that uses spent fuel assemblies and is capable of providing high gamma doses for studies of the effects of radiation on materials.
Neutron Scattering

Neutron scattering can provide information about the structure and properties of materials that cannot be obtained from other techniques such as X-rays or electron microscopes. There are many neutron scattering techniques, but they all involve the detection of particles after a beam of neutrons collides with a sample material. HFIR uses nuclear fission to release neutrons which are directed away from the reactor core and down four steady beams. Three of these beams use the neutrons as they are created (thermal neutrons), and one beam moderates (cools and slows) the neutrons with supercritical hydrogen, enabling the study of soft matter such as plastics and biological materials. The thermal and cold neutrons produced by HFIR are used for research in a wide array of fields of study, from fundamental physics to cancer research. The high neutron flux in HFIR produces the world's brightest neutron beams, which allow faster and higher resolution detection.

7.17.1 Irradiation Materials Testing

HFIR provides a variety of in-core irradiation facilities, allowing for a wide range of materials experiments to study the effects of neutron-induced damage to materials. This research supports fusion energy and next-generation nuclear power programs, as well as extending the lifetime of the world's current nuclear power plants. HFIR has the unique ability to deliver the highest thermal neutron-induced material damage in the nation.

The HFIR Gamma Irradiation Facility is designed to expose material samples to gamma radiation using spent HFIR fuel elements. The facility offers high dose rates and custom sample environments for the most innovative research.

7.17.2 Isotope Production

Isotopes play an extremely important role in the fields of nuclear medicine, homeland security, energy, defense, as well as in basic research. HFIR's high neutron flux enables the production of key isotopes that cannot be made elsewhere, such as ^{252}Ca, ^{75}Se, and ^{63}Ni, among others. Additionally, HFIR will produce ^{238}Pu, which is used to power NASA's deep space missions.

7.17.3 Neutron Activation Analysis

Neutron Activation Analysis (NM) is an extremely sensitive technique used to determine the existence and quantities of major, minor and trace elements in a material sample for applications including forensic science, environmental monitoring, nonproliferation, homeland security, and fundamental research.

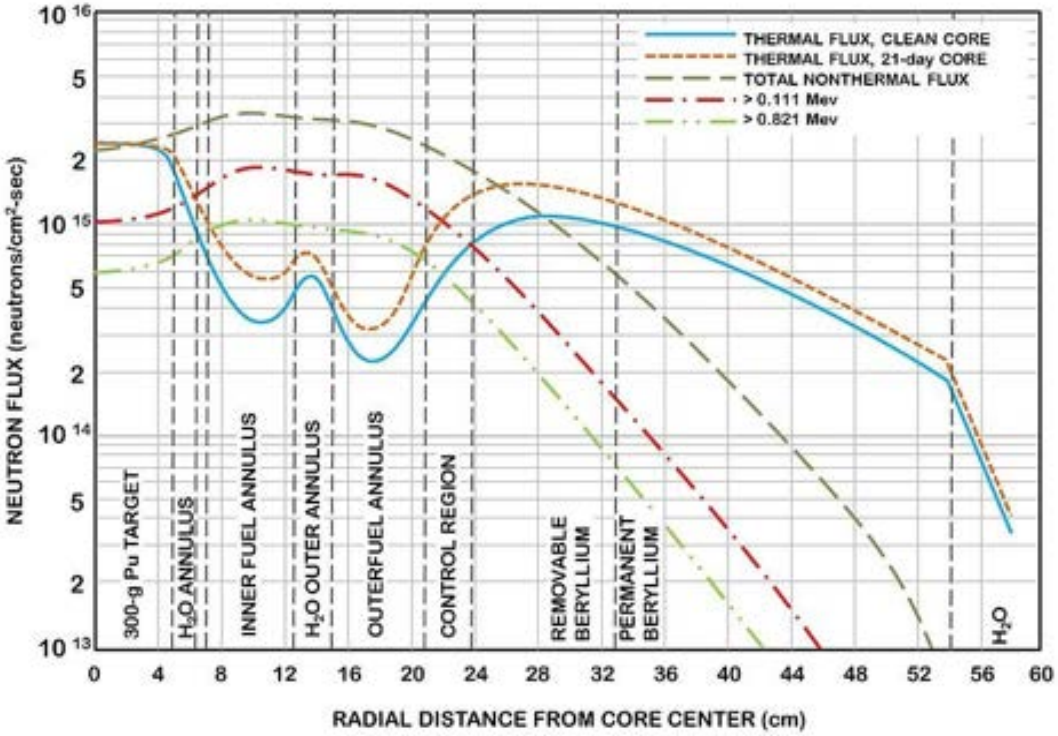

Figure 26. Neutron flux as a function of radial distance from the core centerline.

7.18 A.18: Ohio University, Edwards Accelerator Laboratory

General Description: University-based facility.

Accelerator: High current 4.5-MV T-type Pelletron tandem

Beams: *Neutrons*: 0.5 to 25 MeV
Light particles: ^{1}H, ^{2}H, ^{3}He, ^{4}He, Li, B, C beams

Present detector capabilities: 1-7 detector arrays of NE213 scintillators of 2.5-cm-thick x17.8-cm-diameter or 5-cm-thick x12.7-cm-diameter; lithium glass scintillators; polyethylene moderator with ^{3}He and BF$_3$ proportional counters; a Si strip array for charged-particles; a 10-arm charged particle TOF-E Chamber; and BGO, NaI(Tl), and HPGe gamma detectors.

Research Focus: nuclear astrophysics, nuclear structure, condensed matter physics, and applied nuclear physics.

Contact person: David Ingram (740)-593-1705
ingram@ohio.edu

Prepared by C.R. Brune, D.C. Ingram, and T.N. Massey, and C.E. Parker

7.18.1 Overview

The Edwards Accelerator Laboratory at Ohio University (OU) was originally constructed with funds supplied by the U.S. Atomic Energy Commission and the State of Ohio. The 4.5-MV tandem van de Graaff accelerator was built and installed by the High Voltage Engineering Company, with the first experiments being performed in 1971. The accelerator has a unique T-shape configuration, with the recently installed Pelletron charging system running perpendicular to the acceleration column, which is designed to support high beam intensities. The laboratory was expanded in 1994, and now includes a vault for the accelerator, two target rooms, a control room, a chemistry room, an electronics shop, an undergraduate teaching laboratory, and offices for students, staff, and faculty.

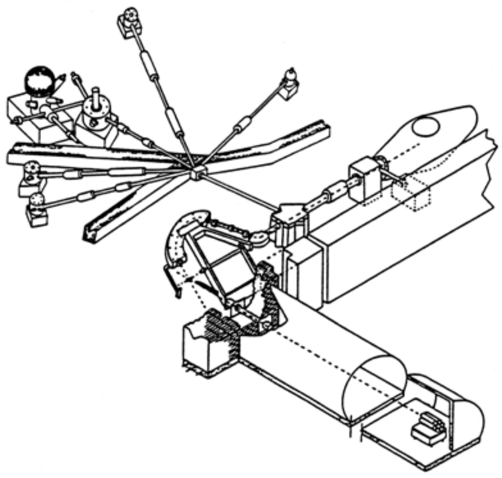

Figure 27. Edwards Accelerator Lab Layout.

The 4.5-MV tandem accelerator and beamlines are shown in Figure 27. This machine is presently equipped with a Cs sputter ion source that is used for the production of proton, deuteron, lithium, boron, and carbon beams. The typical maximum beam current available on target for proton and deuteron beams is 10 μA. A National Electrostatics Corporation Alphatross ion source is available for producing ^{3}He and ^{4}He beams. For these beams, the typical maximum beam current available on target is 0.5 μA. Pulsing and bunching equipment are capable of achieving 1 ns bursts for proton and deuteron beams, 2.5 ns bursts for ^{3,4}He beams, and 3 ns bursts for ^{6,7}Li. The 5 MHz fundamental frequency of our pulsing system leads to 200 ns between pulses. The time between pulses can be increased by discarding pulses using an electronic chopper.

The Edwards Accelerator Laboratory is a unique national facility. An overview of the laboratory is provided in Ref. [1]. The combination of continuous and monoenergetic neutrons together with a well-shielded 30 meter flight path does not exist anywhere else in North America. The beam swinger facility is described in Ref. [2]. This combination of equipment permits measurements with high precision and low background. Several types of neutron detectors are available, including lithium glass, NE213, and fission chambers. The laboratory has the licenses and equipment necessary for utilizing both solid and gaseous tritium targets

7.18.2 Outside Users

Several groups visit the laboratory each year to conduct experiments. Many outside groups utilize our unique neutron time-of-flight capabilities. The arrangements with outside users may or may not be collaborative. In some cases, outside users may pay for beam time.

7.18.3 Specific Neutron Sources

The laboratory has both monoenergetic and “white" neutron sources available for measurements and detector calibrations. The available reactions utilizing gas cells include ^{3}H(p,n), ^{2}H(d,n), ^{3}H(d,n), ^{15}N(p,n), and ^{15}N(d,n). In total these will cover the energy range of 0.5 to 24 MeV with our available proton and deuteron energies. A summary of the neutron production for these reactions is shown in Figure 28. We also have the capability to rapidly cycle between two gas cells, a technique that is very useful for measuring backgrounds [3]. Flight paths of up to 30 m are available.

For some applications, solid targets are desirable. Lower-energy neutrons can be produced by utilizing the (p,n) reaction on thin metallic ^{7}Li or titanium tritide targets. We also commonly produce ~15-MeV neutrons via the ^{3}H(d,n) reaction by bombarding a solid titanium tritide stopping target with a 500-keV deuteron beam (the practical low-energy limit of our accelerator). This configuration generates 2.4 x 10^7 n/sr/μA/s neutrons. In this case, typical beam currents are 1-3 μA, with the beam current being limited by the transmission of the accelerator, which is not optimized for such low-energy beams. We have produced beams up to 25 MeV using a solid tritium target.

7.18.4 Detector Calibration

For calibration of detectors with a “white" source and the time-of-fight technique, a standard has been developed: neutrons at 120° from the 7.44-MeV deuteron bombardment of a thick aluminum target [4]. This standard has been measured relative to the primary standard of ^{235}U fission. We also have a low-mass ^{252}Cf fission chamber that is available for neutron detector calibration

[5]. The shape of the neutron energy spectrum is known to 1-2% accuracy from 1 to 8 MeV neutron energy [6].

7.18.5 Gamma and Charged Particle Capabilities

Gamma-ray detection equipment includes HPGe, BGO, LaBr, and NaI detectors. Charged-particle detection equipment includes a scattering chamber optimized for Rutherford Backscattering and another chamber for time-of-flight measurements with flight paths of up to 2 m. The W.M. Keck Thin Film Analysis Facility consists of an integrated set of UHV chambers that includes PVD and CVD deposition facilities with MeV ion beam analysis (RBS, NRA, ERS, channeling), LEED, and electron spectroscopy (Auger, XPS, UPS).

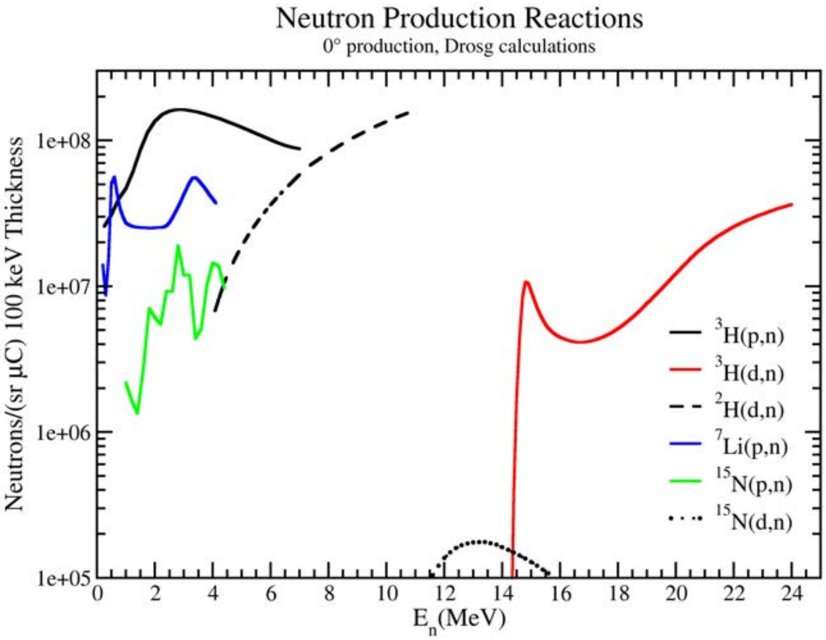

Figure 28. The neutron yield of various neutron production reactions is shown based on a thickness equivalent to a 100 keV energy loss in the target. The calculation is for 100 keV energy loss in the pure gas, except for ^{7}Li, where it is from the pure metal.

7.18.6 References

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7.19 A.19: Rensselaer Polytechnic University, Gaerttner Linear Accelerator Laboratory

linac The Gaerttner LINAC Center

General Description: University based center that specializes in measurements of electron, photon, and neutron induced reactions.

The center is equipped with variety of neutron production targets and detector setups. The center supports external users for a fee.

Accelerator: Electron LINAC Electron beam energy: 9-60 MeV Pulse width: 5-5000 ns Repetition rate: 1-400 Hz
Undergoing an upgrade to 150 MeV with x10 higher intensity

Beams: Neutron beams delivered to several flight path stations from 15-250 m.

Experimental: Neutron induced reactions; photon induced reactions, medical isotope production research, and radiation damage to electronics

Detectors: For setups of neutron transmission, capture, scattering, fission

Includes: organic and inorganic scintillators, ionization chamber, fission chambers, and solid-state detectors.

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Prepared by Yaron Danon

The Gaerttner LINAC Center uses a 60 MeV LINAC to produce short pulses of electrons which are used to produce photons and neutrons. Over the years the facility has been used for a range of research topics, including electron, photon, and neutron interactions, neutron photoproduction, medical isotopes, radiation damage, and applied radiation applications. The accelerator is undergoing an upgrade to increase the electron beam energy to 140 MeV and the short pulse (5ns) power by a factor of 10.

The principal research focus is on nuclear data, primarily related to neutron interactions. The experimental setup is very flexible, providing multiple setups of neutron production targets and neutron detectors, which are designed to optimize a variety of experiments. More information on the facility and examples are available in references [1] and [2].

The motivation of the nuclear data research is applications in nuclear power generation and criticality safety. The LINAC target room has a large space that enables experiments in proximity to the neutron production target as illustrated in Figure 29. To cover the wide range of neutron energies found in nuclear reactor and other criticality applications, measurement capabilities from thermal to 20 MeV were developed with a focus on the resonance region. The measurement capability matrix is shown in Figure 30 as a function of incident neutron energy.

Figure 29. The spacious LINAC target room.

Below we provide short descriptions of current experimental setups.

7.19.1 Neutron Transmission

Neutron transmission experiments include several setups located at different flight path stations, which use different combinations of neutron production targets and detector types to optimize the measurements for a given incident neutron energy range. ***Thermal neutron transmission*** (0.001-20 eV) uses a Li-Glass detector located at 15 m flight path and neutron production from the Enhanced Thermal Target. ***Epithermal neutron transmission*** (1 eV-10 keV) uses a Li-Glass detector located at 35 m flight path station and neutron production from the Bare Bounce Target. ***Mid Energy neutron transmission*** (5 keV -1 MeV) uses an array of Li-Glass detectors located at the 100 m flight path station and neutron production from the Pacman Target. ***High energy neutron transmission*** (0.4-20 MeV) uses an array of liquid scintillators located at 250 m flight path station and neutron production from the Bare Target.

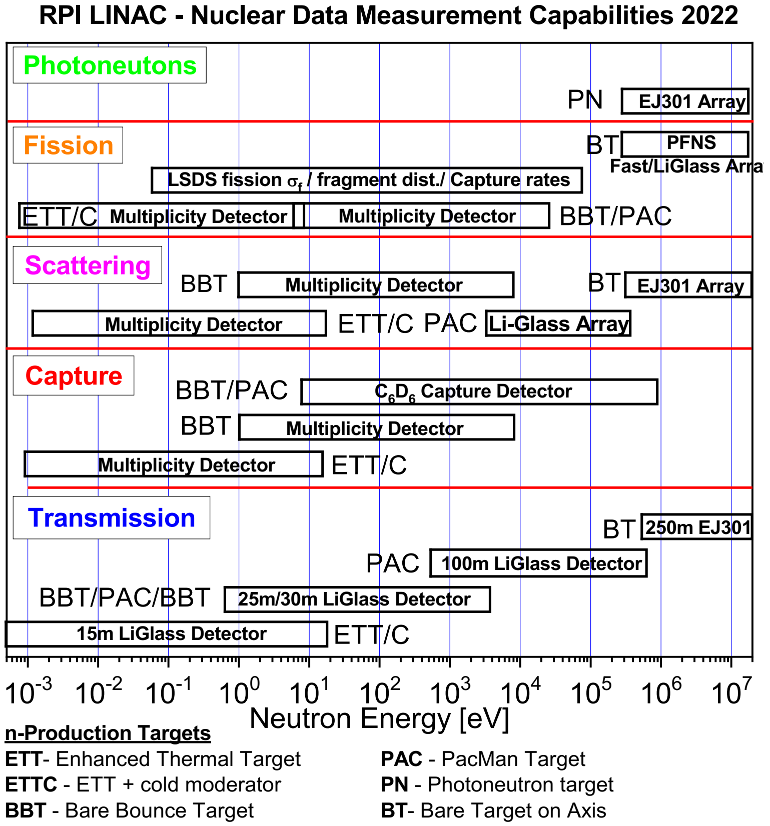

Figure 30. The Gaerttner LINAC Center capability matrix for neutron induced reactions measurements. A keV neutron scattering system is under development.

7.19.2 Neutron Capture

Currently there are two time-of-flight setups for neutron capture measurements:

Low and epithermal energy neutron capture (0.01 eV – 3 keV), uses the neutron multiplicity detector; an array of 16 NaI gamma detectors surrounding the sample. Located at a 25 m flight path and uses the Enhanced Thermal Target or the Bare Bounce Target. This detector also provides capture gamma cascade data.

Mid energy neutron capture (1 eV – 2 MeV) an array of 7 C_6D_6 liquid scintillator gamma detectors designed to measure gammas from neutron capture for incident neutron energy in the keV region where neutron scattering reactions dominated. The array is located at a 45 m flight station and uses the Pacman neutron production target. Figure 31 shows an example of transmission and capture measurements of Re used to generate new resonance parameters [3]. The data were measured using an experimental setup for the thermal region for both transmission and capture measurements.

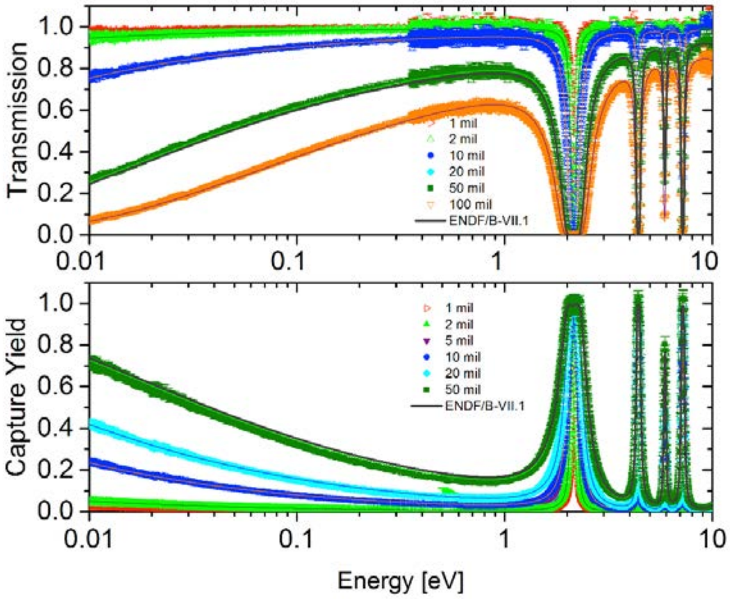

Figure 31. An example of resonance transmission (top) and capture (bottom) measurements on Re. The plot also includes curves generated from fitted resonance parameters and the ENDF/B-VII.1 evaluation [3].

7.19.3 Fast Neutron Scattering

An array of 8 liquid scintillators located at a 30 m flight path station is used for neutron detection. The Bare Target is used for neutron production. The setup is designed to measure neutron scattering in the energy range from 0.5-20 MeV. The detectors use pulse shape analysis to identify photons.

An example of measured neutron backscatter from a ^{238}U sample [4] is shown in Figure 32. This measurement benchmarks both the scattering cross section and the angular distribution.

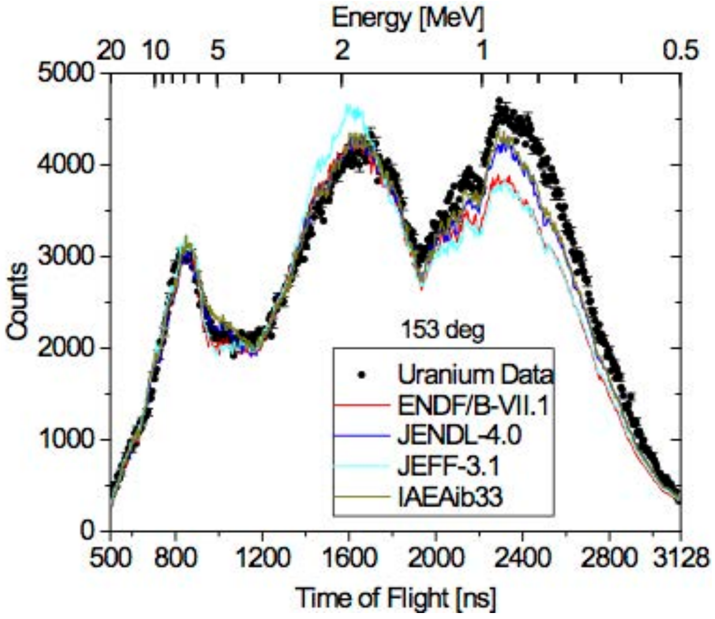

Figure 32. Comparison of experimental data and evaluations for neutron scattering to 153° from a ^{238}U sample [4]. In this case the JENDL 4.0 and IAEA ib33 evaluations perform best

7.19.4 Prompt Fission Neutron Spectrum

This setup utilizes the scattering detector array, with the addition of plastic scintillators and 4 large BaF_2 gamma detectors. The gamma detectors are used to form a fission tag, enabling a double time-of-flight experiment that is used to measure the prompt fission neutron spectrum as a function of incident neutron energy.

7.19.5 Lead Slowing Down Spectrometer

The Lead Slowing-Down Spectrometer (LSDS) is a unique setup, in which the LINAC pulse neutron source is located in the center of a 5.83 m^3 pure lead cube. The neutron slowing down process results in a very high neutron flux, which enables measurements of very small samples (nanograms) or samples with small cross sections (microbarns). The LSDS was used to measure fission cross sections, fission fragment mass and energy distributions, (n,□) and (n,p) cross sections, and capture cross sections.

7.19.6 References

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7.20 A.20: Texas A&M University, Radiation Effects Facility

General Description: Heavy ions and protons for Single Event Upset (SEU) testing, detector calibration, implantations, basic nuclear physics studies, and any other application utilizing low to medium energy particle beams.

Accelerators: K500 Superconducting Cyclotron and K150 (88-in) Cyclotron

Beams: The K500 Superconducting Cyclotron produces heavy ion beams between ~3 – 80 MeV/nucleon and proton beams at 30, 40 and 55 MeV. The K150 (88-in) Cyclotron produces heavy ions from ~3 – 15 MeV/nucleon and protons from 10 – 55 MeV. For SEU testing, three beam energy series are provided: 15 MeV/nucleon (He, N, Ne, Ar, Cu, Kr, Ag, Xe, Pr, Ho, Ta, Au), 25 MeV/nucleon (He, N, Ne, Ar, Kr, Ag, Xe) and 40 MeV/nucleon (N, Ne, Ar, Kr).

Website: http://cyclotron.tamu.edu/ref

Host Location: Cyclotron Institute, Texas A&M University, College Station, TX.

Availability: 24 hours/day, 7 days/week.

Contact person: Henry Clark; clark@comp.tamu.edu; 979-845-1411

Prepared by Henry L Clark

Since 1994, the Cyclotron Institute's Radiation Effects Facility has provided a convenient and low cost solution to commercial, governmental and educational agencies in need of studying, testing and simulating the effects of ionizing radiation on electronic and biological systems. Starting at just 100 hours/year at inception, the demand for beam time has grown to 3000 hours/year and has remained consistent at this level for several years.

The facility is installed on a dedicated beam line with diagnostic equipment for beam quality and complete dosimetry analysis. As a part of the Cyclotron Institute the facility is fully staffed, including electronic and machine shops that are available to assist with special customer needs. Beam time may be scheduled in 8 hours blocks either consecutively or interleaved with other testing groups.

Testing may be conducted in either our 30" diameter vacuum chamber or with our convenient in-air positioning system. Both provide precise positioning in x, y, and z as well as rotations up to 60 degrees in both theta and roll angle. Our custom-made SEUSS software carries out positioning and dosimetry. A degrader foil system makes it possible to change beam energy without cyclotron retuning or target rotations.

Our 15 MeV/nucleon (He, N, Ne, Ar, Cu, Kr, Ag, Xe, Pr, Ho, Ta, Au) series allows testing with Linear Energy Transfer (LET) from 1 – 93 MeV/mg/cm^2 in Si. Our 25 MeV/nucleon (He, N, Ne, Ar, Kr, Ag, Xe) and 40 MeV/nucleon (N, Ne, Ar, Kr) series offer heavy ions for long range testing from 286 µm to 2.3 mm in Si. Typical beam time changes are between 30 minutes to 1 hour.

The beam flux is adjustable between 1E1 – 2E7 ions/cm^2/sec. A higher flux of 1E10 protons/cm^2/sec is obtainable from the K150 cyclotron. The beam spot size is selectable between 0.1 – 2 in. in diameter. Beam uniformity is typically better than 90%.

The beam uniformity and dosimetry are determined by an array of five plastic scintillators coupled to photo multiplier tubes. These scintillators are located in the diagnostic chamber adjacent to and upstream from the target area. The control software determines beam uniformity, axial gain, and beam flux (in particles/cm^2/sec), based on scintillator count rates. The results are displayed and updated once per second.

7.21 A.21: Triangle Universities Nuclear Laboratory (TUNL)

General Description: DOE Center of Excellence in nuclear physics consisting of four universities: Duke University, NC Central University, NC State University, and The University of NC at Chapel Hill. Primary research includes nuclear structure, nuclear astrophysics, low-energy QCD, fundamental symmetries and neutrino studies. TUNL operates three accelerator facilities: the High Intensity Gamma-ray Source (HIGS), the Laboratory for Experimental Nuclear Astrophysics (LENA), and the Tandem Laboratory. Collectively these facilities enable measurements using g-ray, fast-neutron and light-ion beams.

HIGS: Quasi-monoenergetic photon beams are produced by Compton backscattering of photons from relativistic electron bunches circulating inside the optical cavity of a storage-ring based free-electron laser (FEL). The HIGS delivers circularly and linearly polarized beams in the energy range of 1.5 to 120 MeV to experiments. HIGS consists of a 160 MeV Linac injector, a 1.2 GeV booster synchrotron, a 1.2 GeV electron storage ring equipped with undulator magnets to provide linearly and circularly polarized FEL photons. The gamma-ray beam energy spread is adjustable down to about 1.5% FWHM through collimation. Typical collimator size: 3/4" dia., resulting in DE/E ~ 3% and between 10^7 and $3x10^8$ g-rays per second. HIGS is the world's most intense Compton g-ray source, with 10^3 g /(eV s).

LENA: Proton accelerator facility for measuring nuclear reactions at low energies for astrophysics studies. The upgraded facility will consist of a 230-kV high-current ECR ion source and a 2-MV Singletron accelerator by HVEE with the following properties:

ECR: I_{max}=20 mA dc;
slow pulsing capability (10% duty cycle)

Singletron:
TV = 1 - 2 MV, I_{max} = 2 mA dc;
Pulsing: 0.125 – 2.0 MHz with Dt = 2 – 20 ns

Tandem: FN 10-MV tandem accelerator with ion sources to accelerate p, d, ^{3}He and ^{4}He ions. Pulsed beam operation (1.5 to 3 ns time resolution) at 2.5 MHz or reduced repetition rate. An upgrade of the low-energy beam injector system is underway. The design performance specifications of the new system are:

- NEC TORVIS:

  I_{max} = 100 mA H^- or D^- dc
  I_{max} = 20 mA $^4He^-$ or $^3He^-$ dc
  I_{max} for pulsed beam □ 10% Imax dc

- NEC SNICS-II:

  Produces a wide variety of elemental ion beams

Secondary beams: Mono-energetic or quasi mono-energetic neutrons in the 0.1 MeV to 35 MeV neutron energy range using the reactions ^{7}Li(p,n)^{7}Be, ^{3}H(p,n)^{3}He, ^{2}H(d,n)^{3}He and ^{3}H(d,n)^{4}He with neutron fluxes up to 10^8 n/(cm^2 sec) at 1 cm distance from the neutron source in dc operation and up to 3 x 10^7 n/(cm^2 sec) in pulsed mode operation.

Collimated neutron beam with adjustable cross sectional area (up to 6 cm in diameter) and 10^4 n/(cm^2 sec) on targets in the 4 to 20 MeV neutron energy

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The research conducted in the three accelerator facilities at TUNL produces data that are representative of results produced at the frontiers of nuclear structure, nuclear astrophysics, nuclear fission, and low-energy QCD. The floor layout and photographs of the facilities are shown in Figures 33 – 37. In addition, the unique and world-leading beam capabilities and research instrumentation of these facilities enable research that is motivated by applications, e.g., in nuclear security, fusion energy, particle detector development, homeland security, medical isotope production, and radiation effects on electronics.

The nuclear security and fusion-energy research are conducted in collaboration with scientists from LANL and LLNL and focuses on neutron- and gamma-ray induced reactions on actinide nuclei, especially fission and neutron-induced reactions relevant to nuclear forensics. Also, a substantial component of the applied work is aimed at providing new insights relevant to understanding the complex physics governing the inertial confinement DT fusion plasma at the National Ignition Facility (NIF) at LLNL.

The applied research is carried out using the neutron beams in the tandem lab and the photon beam at HIGS. The research instrumentation available for this work includes silicon detectors for charged particle detection, HPGe detectors for high-resolution g-ray spectroscopy, ^{3}He gas scintillators and ionization chambers for low-energy neutron detection, liquid scintillators for fast neutron detection (including the neutron time-of-flight spectrometer shown in Figure 38). Collimated neutron beams are available in the tandem lab at the neutron shielded source shown in Figure 39. There are **RA**pid **B**elt-driven **I**rradiated **T**arget **T**ransfer **S**ystems (RABITTS) that are optimized for activation measurements, including measurements of fission product yields. A diagram is shown in Figure 40. Also, an Enge split-pole spectrometer in the tandem lab is available for special applications.

Recent nuclear physics applications at the tandem laboratory included neutron-induced fission product yield measurements on ^{235}U, ^{238}U and ^{239}Pu between 0.06 and 15 MeV, and cross section measurements involving the reactions ^{235}U(n,n'γ), ^{238}U(n,n'γ), ^{241}Am(n,2n)^{240}Am, ^{181}Ta(n,2n)^{180}Ta, ^{124,136}Xe(n,2n)^{123,135}Xe and neutron capture on a number of nuclei, including ^{124,136}Xe(n,γ)^{125,137}Xe,

Recent nuclear physics applications at HIGS concentrated on cross-section measurements of ^{241}Am(γ,n)^{240}Am, ^{235}U(γ,γ')^{235}U, ^{238}U(γ,γ')^{238}U, ^{239}Pu(γ,γ')^{239}Pu, ^{240}Pu(γ,γ')^{240}Pu and ^{235}U(γ,f), ^{238}U(γ,f), and ^{239}Pu(γ,f).

7.21.1 References

1. W. Tornow, Nuclear Physics News International, Vol. 11 (4), 6 (2001).
2. H.R. Weller, M.W. Ahmed, H. Gao, W. Tornow, Y.K. Wu, M. Gai, R. Miskimen, Progress in Particle and Nuclear Physic 62, 257 (2009)

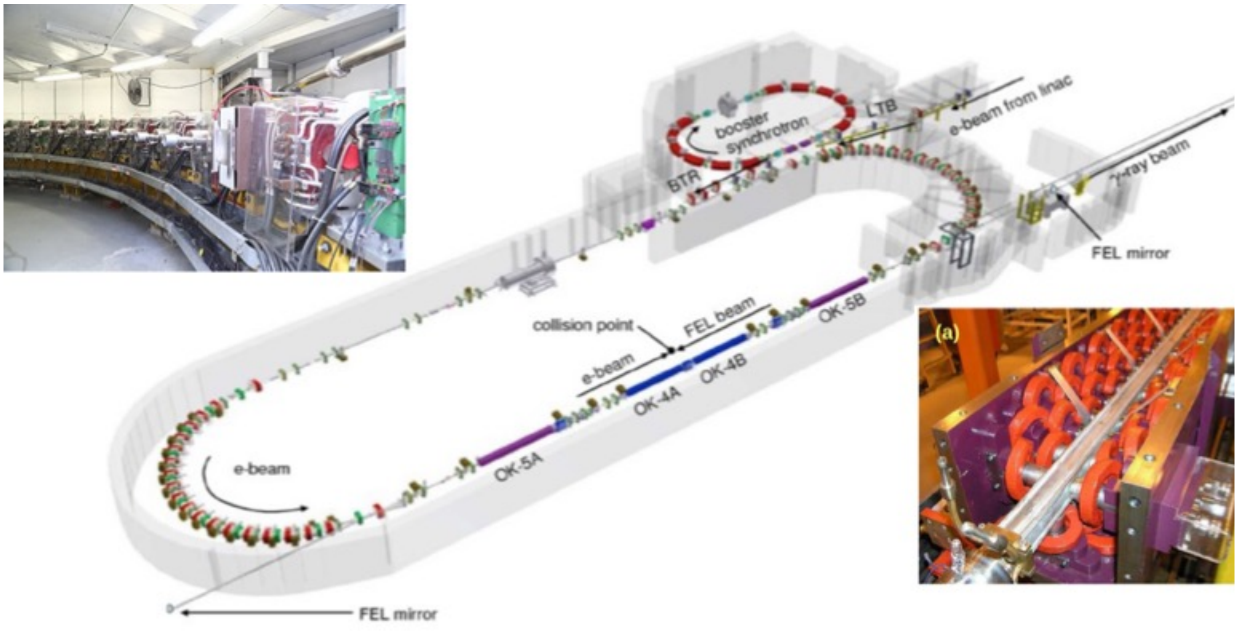

Figure 33. Layout of the HIGS accelerator systems. Upper left: Photograph of a section of one arc of the storage ring. Lower right: photograph of one of the helical undulator magnets used to produce circularly polarized light.

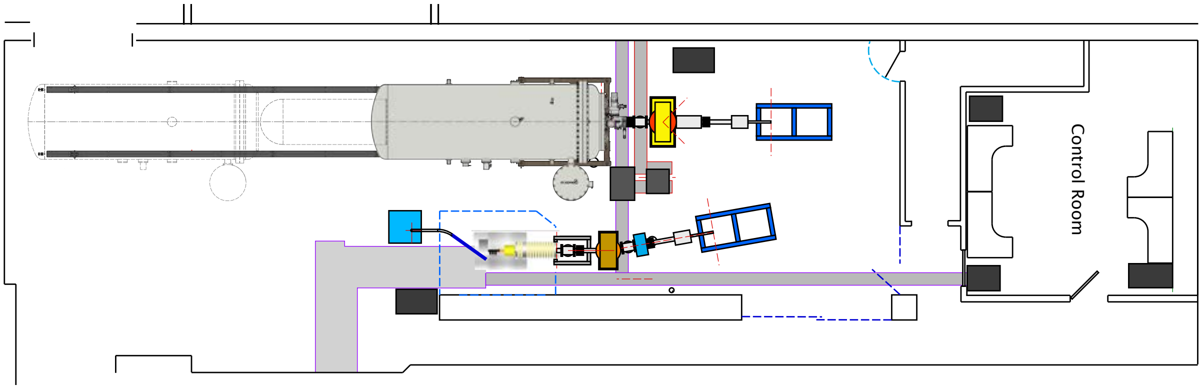

Figure 34. Floor layout for the upgraded LENA.

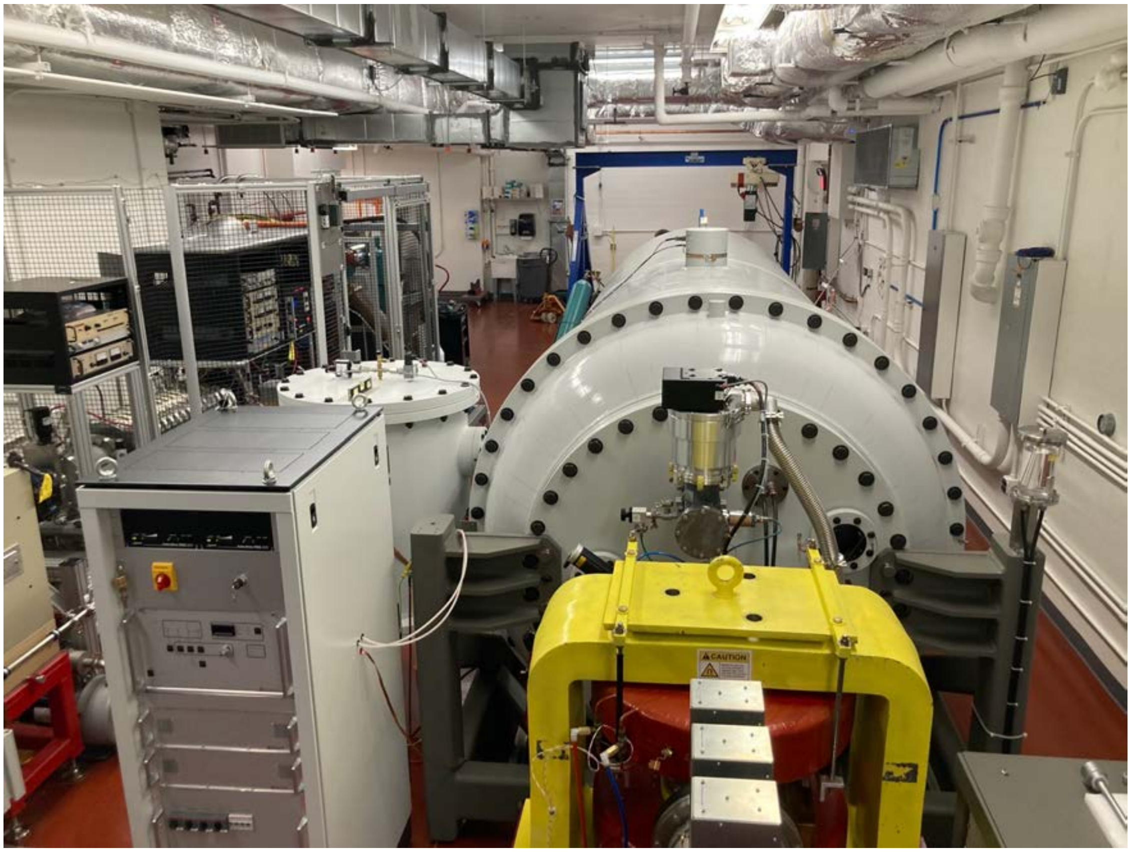

Figure 35. Photograph of the upgraded LENA. The photograph is taken looking from the control room toward the Singletron.

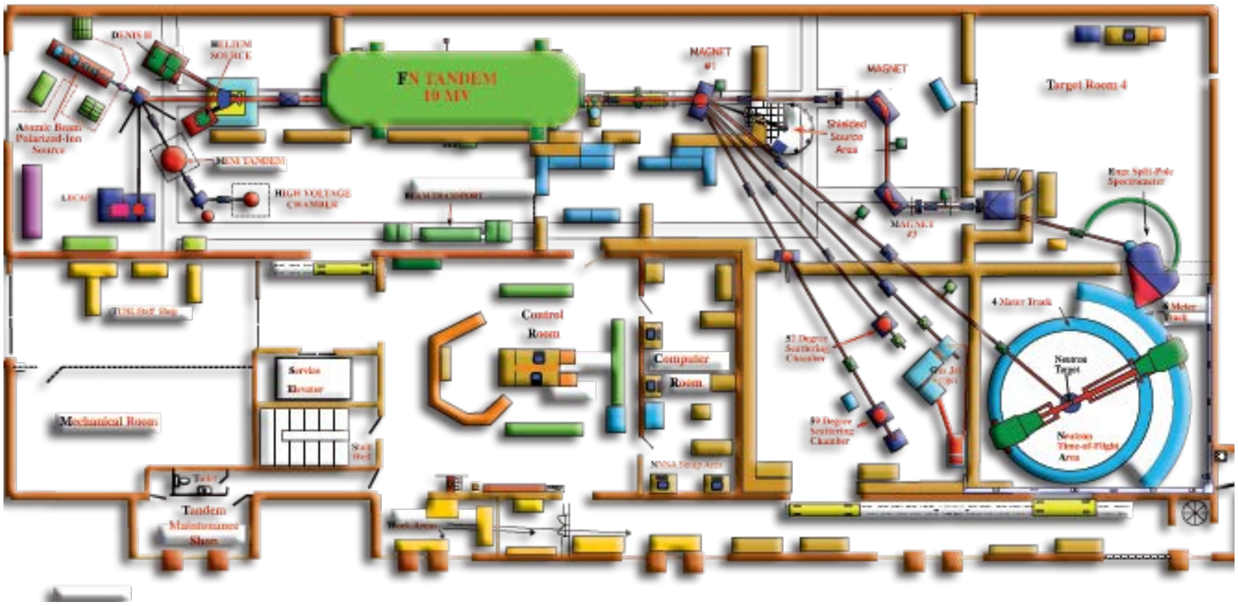

Figure 36. Tandem accelerator laboratory floor plan.

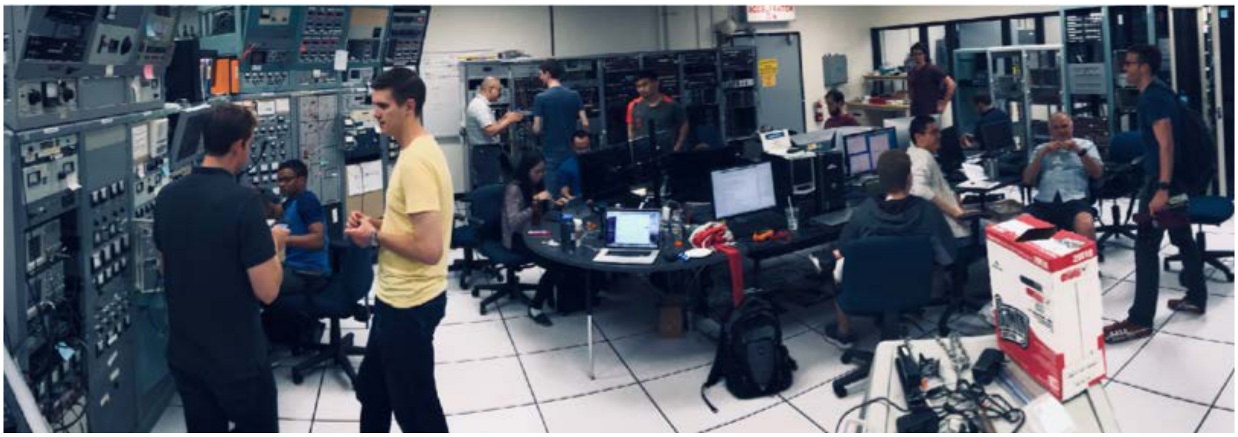

Figure 37. Photograph of the tandem accelerator control room.

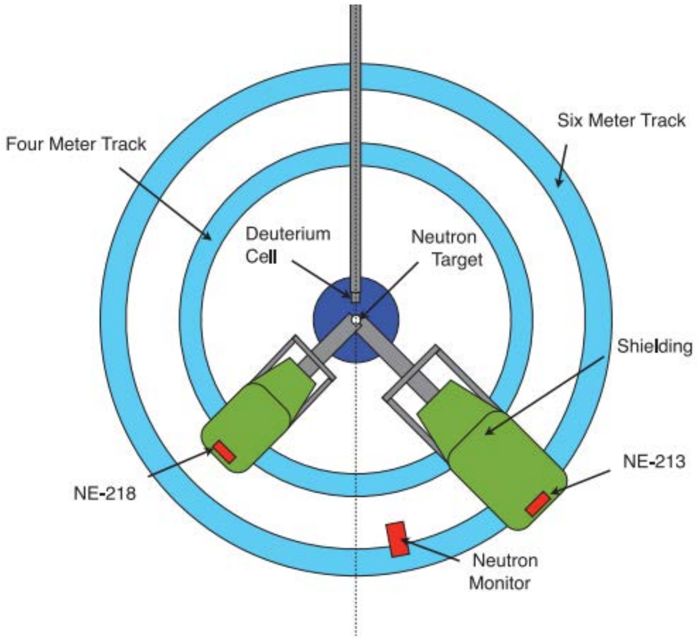

Figure 38. Neutron Time-of-Flight spectrometer in the tandem lab.

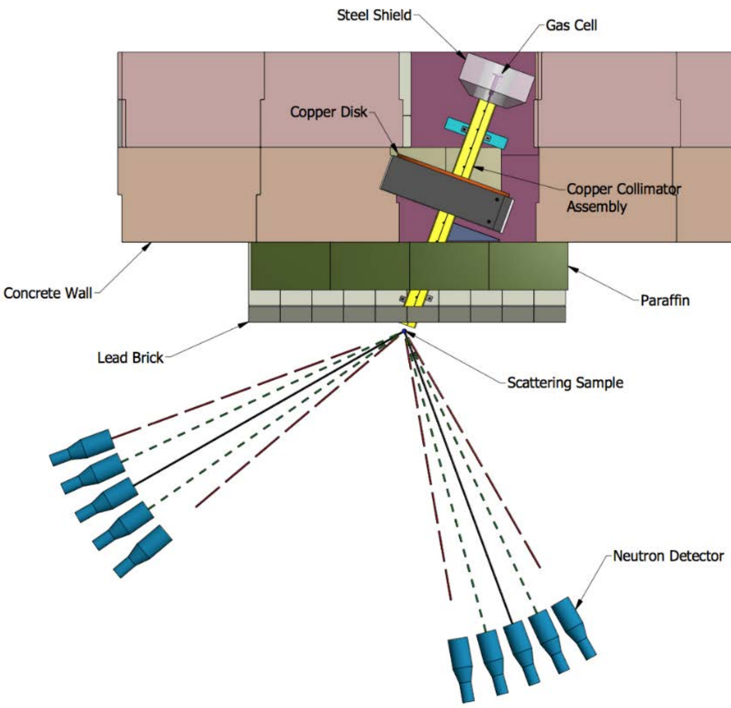

Figure 39. Shielded neutron source area for collimated neutron beams in the tandem lab.

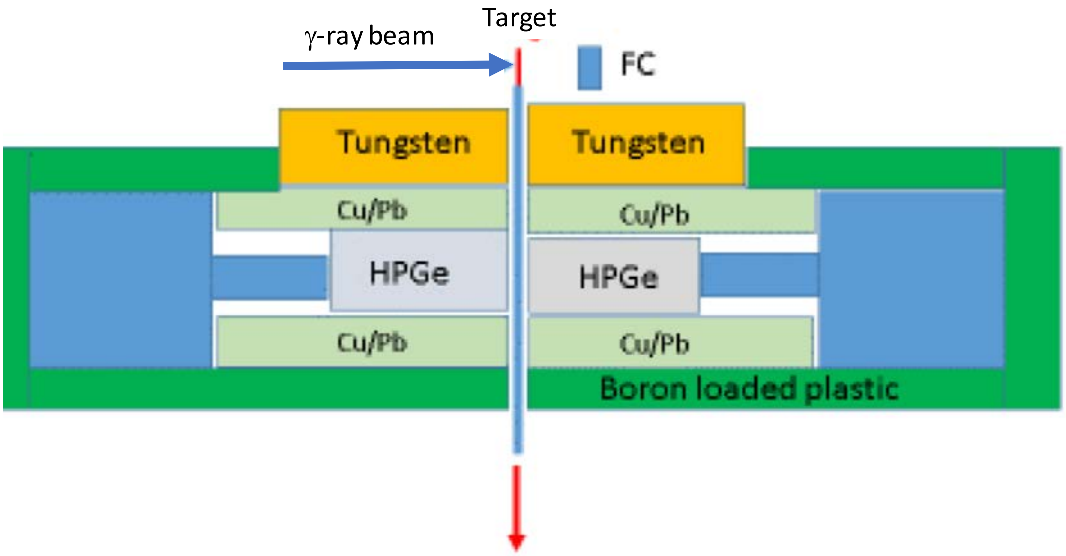

Figure 40. Diagram of the **RA**pid **B**elt-driven **I**rradiated **T**arget **T**ransfer **S**ystem (RABITTS) used for activation measurements, including fission product yields. There are two RABITTS at TUNL: one with a 10-m long track in the tandem lab and one with a 1-m long track at HIGS.