

WHITE PAPER ON NUCLEAR STRUCTURE, REACTIONS, AND ASTROPHYSICS



NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions, and Astrophysics
November 14–16, 2022, Argonne National Laboratory

WHITE PAPER ON NUCLEAR STRUCTURE, REACTIONS, AND ASTROPHYSICS

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EXECUTIVE SUMMARY OF THE NUCLEAR STRUCTURE, REACTIONS, AND ASTROPHYSICS TOWN MEETING

In preparation for the 2023 NSAC Long Range Plan (LRP), the DNP Town Meeting on Nuclear Structure, Reactions, and Astrophysics was held at Argonne National Laboratory (ANL) on Nov 14-16, 2022. The town meeting brought together 578 members of the low-energy nuclear science community, including 216 in-person attendees and 362 remote participants coming from US national laboratories, a wide range of US universities and other research institutions and universities abroad. Participants met in five topic-oriented and seven cross-cutting and intersecting working groups to discuss progress since the 2015 LRP and identify compelling science opportunities and the resources needed to realize them. These considerations were used during the Town Meeting to determine a set of resolutions outlining the highest priorities for our subfield. The full text of the resolutions endorsed by unanimous consent by the low-energy nuclear science community at the Town Meeting is presented at the end of this executive summary. The reports from all working groups that met during the Town Meeting are included as Secs. 1 to 11 of this Whitepaper.

The intellectual challenges for nuclear structure, reactions and astrophysics can be captured in the following questions:

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes, and how do the rich phenomena of nuclear structure and reactions emerge?
- How do single-nucleon, cluster, and collective degrees of freedom coexist and evolve with increasing proton-neutron imbalance and excitation energies?
- What are the limits of nuclear existence, and what features arise near and beyond these limits?
- What are the astrophysical origins of the elements and how did the associated chemical evolution proceed?
- How do stars evolve, and what nuclear signatures do they leave behind?
- What is the nature of neutron stars and dense matter?
- How can the knowledge and technological progress provided by nuclear science best be used to benefit society?

Answering these questions requires a comprehensive and forward-looking research program in nuclear structure, reactions, and astrophysics with experiment and theory working in concert. Its core objectives are to arrive at a predictive understanding of the properties of atomic nuclei and their behavior in nuclear decays and reactions; chart the limits of their existence; reveal the underlying nuclear physics of stars, stellar explosions, and element synthesis in the cosmos; leverage the properties of nuclei to enable precision tests of nature's fundamental symmetries; apply nuclear science for societal benefit; and provide accessible, state-of-the-art, accredited nuclear data to advance nuclear science and its broad applications. These goals are highly integrated and entangled with each other, all essential to maintaining U.S. leadership in nuclear science for the coming decade.

Fueled by the rapidly growing landscape of accessible nuclei at national user and university-based facilities delivering beams of stable and rare isotopes, by the advent of multi-messenger astronomy, and by major advances in low-energy nuclear theory, astrophysics modeling and high-performance computing, a comprehensive understanding of the atomic nucleus and its role in the Universe is now within reach. Continuous Innovation in experimental techniques and instrumentations combined with breakthroughs in the theoretical description of nuclei and in the

systematic estimation of its uncertainties occurred since 2015 now provide a robust framework to extract information about fundamental interactions from low-energy nuclear physics measurements and inspire future experiments. The interpretation of multi-messenger signals from the first neutron-star merger event, using state-of-the-art astrophysics models informed by realistic nuclear properties through experimental and theoretical nuclear physics research, has provided new clues about how the heaviest chemical elements come into being and evolve. The identification of key similarities between the structure, dynamics, and phases of strongly interacting nucleons in nuclei and neutron stars, and cold atomic gases and condensed matter systems has greatly broadened the impact of low-energy nuclear structure and reaction physics during the past seven years. Building on this forward momentum, the nuclear science community looks at the next decade with great optimism and excitement. The wealth of new data expected from the Facility for Rare Isotope Beams (FRIB), the Argonne Tandem Linear Accelerator System at Argonne National Laboratory (ATLAS), and the Association for Research at University Nuclear Accelerators (ARUNA) facilities, neutrino experiments, gravitational waves, and detection of their associated electromagnetic counterparts, and from neutron-star and stellar observations, combined with advances in theory and computing, and with emerging artificial intelligence (AI), machine learning (ML), and quantum information science and technologies provide unprecedented opportunities for fundamental discoveries with broad implications throughout physics and astrophysics.

To realize this scientific vision and to fulfill the broader societal needs for a skilled workforce, low-energy nuclear science must grow and cultivate a more diverse community in which everyone feels welcome, and where each member treats all others with dignity and respect. The work of creating and sustaining a diverse, equitable, inclusive, and welcoming community in nuclear science is the responsibility of every member of our community. All members of the community need to be agents of change for any real progress to be achieved.

Based on this, the Town Meeting participants unanimously endorsed the following affirmation: **Our community affirms in the strongest possible terms its commitment to foster a diverse and equitable workforce and to support and respect diversity in all its forms. Individually and collectively, we commit to ensuring an inclusive and accessible environment for all and taking action if these values are not being upheld.**

Investments in national user and university-based facilities delivering beams of stable and rare isotopes, state-of-the-art instrumentation, and initiatives have laid the foundation for the scientific output of our field for the next decade. A healthy and robust experimental and theoretical research program in nuclear physics and astrophysics, upgrades and new instruments, and the development and retention of a diverse and equitable workforce are now needed to capitalize on these investments and accelerate progress toward achieving the broad science goals of our community and preparing for the longer-term future of nuclear science.

The base program of individual and small research groups constitutes the foundation of our scientific enterprise. Experimental groups across academia and national laboratories are critical to advance research at the user facilities and ARUNA laboratories and ensure their success, through indispensable contributions to experimental motivation and design, equipment developments, and analysis and interpretation of data. In nuclear theory, research groups, often led by a single or a few principal investigators, are the wellsprings of new ideas and innovations, developing models to drive our scientific progress towards a predictive understanding of nuclei and their role in the universe, providing motivation and interpretation for experimental campaigns, and forging new frontiers for the future of the field. The base program is a crucial source of support for graduate students and postdocs and can be effectively leveraged to enhance diversity and inclusion in the nuclear science workforce. The number of people currently being trained and educated in nuclear science is insufficient to meet the workforce needs of academia and research laboratories—including national laboratories—industry, and other sectors. Attracting and retaining highly qualified

persons from all groups, including those presently underrepresented in nuclear science, is a community effort. Healthy funding for the base program and the support of graduate students are thus essential for the continued production of inventive research and for the recruitment, education, and training of the next generation of nuclear scientists.

FRIB and ATLAS are the nation's flagship user facilities for rare-isotope and stable beam experiments. FRIB started user operations in May of 2022 with the first results on never-before-measured β -decay half-lives already published. The already exciting science opportunities are increasing as the primary beam power ramps up and new beams and instruments become available for experiments, advancing our knowledge towards the limits of nuclear existence. Concurrently, the ATLAS facility is entering a new and exciting period, offering a broad set of new science opportunities through nuCARIBU, the N=126 factory (which will enable access to the neutron-rich region of the nuclear chart below ^{208}Pb , critical for understanding the last abundance peak in the rapid neutron capture process or r-process), and the multi-user upgrade coming online. Both user facilities are heavily oversubscribed, demonstrating the keen interest and unwavering enthusiasm of the national and international low-energy nuclear physics user community. Lawrence Berkeley National Laboratory (LBNL) and the NNSA-funded Los Alamos Neutron Science Center (LANSCE) at Los Alamos National Laboratory (LANL) are additional national facilities, offering unique opportunities to the community for the production and study of heavy and superheavy elements and neutron-induced reactions of broad relevance for nuclear science and applications, respectively. For the upcoming Long Range Plan period, to continue and expand leadership in the field of the study of the heaviest isotopes, the US Heavy Element community presented a joint roadmap to capitalize on the unique opportunities arising in the US, including at the LBNL, ATLAS and Texas A&M University accelerator facilities and at ORNL.

The Association for Research at University Nuclear Accelerators (ARUNA) is a consortium of 13 university-based accelerator laboratories in the United States. These laboratories provide essential complementary and often unique capabilities which significantly enhance the national portfolio of nuclear physics facilities. The ARUNA laboratories produce groundbreaking science by pursuing research in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear science applications. The strategic position of the ARUNA laboratories, embedded into the diverse and multifaceted university communities, makes them natural conduits for cross-cutting interdisciplinary research and focal points for attracting and educating the next generation of the nuclear workforce. About 20% of all national graduate degrees in experimental nuclear physics are awarded to ARUNA institution graduates. More than a hundred undergraduate students perform research in ARUNA labs every year. We must maintain and strategically strengthen research efforts at ARUNA labs and enhance ARUNA facilities by investing in new tools and capabilities. It is a cost-effective strategy to support cutting-edge research in universities and ensure the development of a thriving, highly skilled workforce for nuclear science.

Complementary to the Institute for Nuclear Theory (INT), which greatly benefits the broader theory community and nuclear physics, the FRIB Theory Alliance (TA) is a success story that must continue and evolve. This is a national effort born out of the last LRP to foster advancements, attract young talent, and stimulate interdisciplinary collaborations in theory related to diverse areas of science relevant to the FRIB experimental program. Currently, the TA counts almost 300 members, comprising both national and international scientists, and carries out a range of successful initiatives, including the National FRIB Theory Fellow, Bridge Faculty, Topical, and Visiting Scientist programs, that have been instrumental in enhancing the field of low-energy nuclear science. Since its inception, the TA funded bridge positions for five faculties, two of whom have gone on to win Early Career awards. The nine young scientists so far selected to participate in the FRIB Theory Fellow program until now have produced excellent research and seven of them have already secured permanent positions at prominent institutions in the field.

Meanwhile, other activities of the TA such as Topical Programs, Summer Schools, and Dialogs, promote intellectual engagement of researchers at all career stages with key problems in our field. Now that FRIB is online, continued support for the TA is essential to continue to promote a strong coupling between theory and experiment and accelerate progress toward achieving the broad science goals of the low-energy nuclear science community.

Hence, the first resolution was: **The highest priority for low-energy nuclear physics and nuclear astrophysics research is to maintain U.S. world leadership in nuclear science by capitalizing on recent investments. To this end, we strongly support:**

- **Robust theoretical and experimental research programs and the development and retention of a diverse and equitable workforce;**
- **The optimal operation of the FRIB and ATLAS national user facilities;**
- **Investments in the ARUNA facilities, and key national laboratory facilities;**
- **The FRIB Theory Alliance and all its initiatives.**

All are critical to fully realize the scientific potential of the field and foster future breakthroughs.

With FRIB completed on time and within budget, providing beam to users and ramping up power, the low-energy nuclear science and astrophysics community seized the opportunity and looked towards the future of the DOE Office of Science's newest user facility. The field has developed the compelling science case for FRIB400, the energy upgrade of the FRIB linear accelerator to 400 MeV/u (for uranium and higher energies for lighter beams), and now recommends starting the upgrade during the upcoming LRP period to capitalize on the significant discovery potential and scientific opportunities that FRIB400 will bring to the field. Space in the FRIB tunnel was left during construction and the upgrade can be accomplished in stages during regular shutdowns and without significant interruption of the user program. Every stage will enable energy gains. The team is in place and the technology has been proven. The scientific returns from FRIB400 above those being realized initially at FRIB are manifold: (i) significant gains in isotope yields will be realized, nearly doubling the reach of FRIB along the neutron dripline and bringing into reach more nuclei relevant for the r-process and neutron-star crust processes; (ii) dense nuclear matter will be created and studied up to twice the saturation density, a regime critical for interpreting the multi-disciplinary field of multi-messenger astrophysics; (iii) in experiments, up to two-orders-of magnitude increase in luminosity will enable spectroscopy in key regions of the nuclear chart where observables will fuel our understanding of rare isotopes; and (iv) the upgrade will enable experiments at higher energies, where relevant reaction theory models and their approximations have proven to be more accurate thus improving theoretical interpretation.

On the instrumentation side, the Town Meeting participants acknowledged the near completion of the Gamma-Ray Energy Tracking Array (GRETA) project and the first significant funding for the High Rigidity Spectrometer (HRS). The community eagerly awaits their expeditious completion. Both were called out in the previous LRP as "essential to realize the scientific reach of FRIB". In light of this great progress, the community continues to strongly support the development of community devices and named the FRIB Decay Station (FDS) and the isochronous spectrometer with large acceptance (ISLA) as their flagship examples. The FDS will evolve from the existing, already very successful, FDS initiator (FDSi) to provide unmatched decay spectroscopy opportunities. ISLA is envisioned by the community to become the workhorse recoil separator at FRIB's ReA6-12 facilities, enabling broad nuclear structure and astrophysics studies with experiments induced by reaccelerated beams.

Therefore, in the second resolution, the Town Meeting participants unanimously recommend: **The science case for an energy upgrade of FRIB to 400 MeV/u is compelling. FRIB400 greatly expands the opportunities in the field. We strongly endorse starting the upgrade during the upcoming Long Range Plan period to harness its significant discovery potential. We support instrument developments, including the FDS and ISLA now that GRETA and HRS are underway. These community devices are important to realize the full scope of scientific opportunities.**

Computing is essential to all areas of nuclear science, enabling state-of-the-art calculations, simulations, and analyses for experimental and theoretical nuclear physics, accelerator operations, and astrophysical observations. High-performance computing (HPC) was recognized in the 2015 LRP as the “third leg of this field”, and the forefront scientific grand challenges and opportunities offered by the advent of Exascale computing—together with priority research directions and computational resource and workforce requirements—were identified in the 2017 *Nuclear Physics Exascale Requirements Review*. Since then, the ever-increasing computational power of emerging architectures, combined with simultaneous advances in applied mathematics, software and data, and nuclear physics itself, accelerated scientific discovery and transformed the field of low-energy nuclear science. High performance computing has now entered the Exascale era with Frontier at the Oak Ridge Leadership Computing Facility (OLCF) and ANL’s Leadership Computing Facility (ALCL). These and future advanced computing architectures promise unprecedented progress in our understanding of nuclear phenomena but also bring significant new challenges for their effective utilization. In addition, new technologies have given rise to entirely new paradigms for computing that were not available a decade ago. AI and ML are being used to uncover correlations and patterns in data, accelerate calculations, make predictions with reliable error estimates, and automate machine operations. Quantum computing (QC), with the large information capacity of quantum bits (qubits) and its inherent quantum mechanical nature, holds the potential for addressing long-unsolved challenges in our understanding of large quantum systems and dynamical processes. To accelerate discoveries and maintain U.S. leadership, in the next decade we must harness these new technological developments. This will require strengthening existing and forming new programs and partnerships, developing a diverse and equitable workforce at the nexus of nuclear science, computer science, mathematics, statistics, and information sciences, and providing expanded access to hardware and resources, including ‘capacity computing’ at mid-sized HPC machines, ‘capability computing’ with Exascale HPC systems as well as state-of-the-art quantum computing.

These needs were captured in a third, unanimously endorsed resolution: **Computing is essential to advance all fields of nuclear science. We strongly support enhancing opportunities in computational nuclear science to accelerate discoveries and maintain U.S. leadership by:**

- **Strengthening programs and partnerships to ensure the efficient utilization of new high-performance computing (HPC) hardware and new capabilities and approaches offered by artificial intelligence/machine learning (AI/ML) and quantum computing (QC);**
- **Establishing programs that support the education, training of, and professional pathways for a diverse and multidisciplinary workforce with cross-disciplinary collaborations in HPC, AI/ML, and QC;**

Expanding access to dedicated hardware and resources for HPC and new emerging computational technologies, as well as capacity computing essential for many research efforts.

There are clear and well documented benefits of cross-cutting interdisciplinary enterprise. Research centers create an environment and infrastructure for such collaborations. They serve as conduits for bringing together researchers from different fields of knowledge, focusing their efforts on solving hard outstanding problems. They also provide unique opportunities for holistic, multifaceted workforce development. Research centers are particularly important

in such inherently inter-disciplinary areas as nuclear astrophysics. The JINA and JINA-CEE centers, funded by NSF in the past, became recognized national and international hubs for nuclear astrophysics research. We strongly endorse a nuclear astrophysics center that builds on the past success and propels further innovation in the era of multi-messenger astronomy.

As a result, the nuclear science community present at the Town Meeting unanimously endorsed the following fourth resolution: **Research centers are important for low-energy nuclear science. They facilitate strong national and international communications and collaborations across disciplines and across theory and experiment. Interdisciplinary centers are particularly essential for nuclear astrophysics to seize new scientific opportunities in this area. We strongly endorse a nuclear astrophysics center that builds on the success of JINA, fulfills this vital role, and propels innovation in the multi-messenger era.**

Nuclear data is ubiquitous in nuclear science and in modern society. It forms the cornerstone of low-energy fundamental nuclear physics and nuclear astrophysics while providing vital input to a wide range of medical, non-proliferation, homeland security, and industrial applications. To meet the needs of the basic and applied nuclear science communities, evaluated nuclear data must be reliable, credible, up-to-date, comprehensive, and accessible. US-based nuclear data efforts play a world-leading role in the collection, evaluation, and dissemination of nuclear data. A critical issue is to maintain a high level of expertise in nuclear data evaluation to assure sufficient breadth and quality of the nuclear databases and to meet the requirements of a continuously developing user community. These needs can only be accomplished through the continued funding of modern tools and infrastructure along with a firm commitment to hiring and training a diverse nuclear data community.

These considerations led to the fifth and final, unanimously endorsed resolution of the Town Meeting: **Nuclear data play an essential role in all facets of nuclear science. Access to reliable, complete and up-to-date nuclear structure and reaction data is crucial for the fundamental nuclear physics research enterprise, as well as for the successes of applied missions in the areas of defense and security, nuclear energy, space exploration, isotope production, and medical applications. It is thus imperative to maintain an effective US role in the stewardship of nuclear data.**

- **We endorse support for the compilation, evaluation, dissemination and preservation of nuclear data and efforts to build a diverse, equitable and inclusive workforce that maintains reliable and up-to-date nuclear databases through national and international partnerships.**
- **We recommend prioritizing opportunities that enhance the prompt availability and quality of nuclear data and its utility for propelling scientific progress in nuclear structure, reactions and astrophysics and other fundamental physics research programs.**

We endorse identifying interagency-supported crosscutting opportunities for nuclear data with other programs that enrich the utility of nuclear data in both science and society.

The full text of the resolutions unanimously endorsed at the Town Meeting can be found at the end of the Executive Summary. A snapshot of our field, its accomplishments, vision, and synergies is provided below. A more comprehensive discussion of the broad scientific opportunities and challenges for low-energy nuclear structure, reactions and astrophysics can be found in the individual reports from the working groups, included in Secs. 1to11.

In conclusion, the low-energy nuclear science community comprises a dynamic and skilled workforce. The members of this community, with diverse educational backgrounds and research interests, assembled at Argonne National Lab during its first snowstorm of the season to discuss exciting science from the past seven years and to look to the future. We agree that a broad research program at a diverse array of institutions is essential to enable discovery in

an era when a wealth of new data is expected. The sum of the large- and small-scale facilities, together with theory, computing, and data efforts, and the development and growth of a world-leading, diverse workforce will ensure the vitality of our community. FRIB and its key FRIB400 upgrade will provide access to the extremely neutron-rich isotopes required to build a more complete picture of nuclear matter and its role in the Cosmos. The varied and complementary suite of beams and specialized tools provided by ATLAS are critical to the overall success of the research community. The ARUNA laboratories offer unique, specialized facilities and research opportunities, while providing outstanding training for the next generation of nuclear scientists. Primarily undergraduate and minority serving institutions are essential pillars for developing a robust and diverse workforce. Key national laboratory facilities contribute targeted capabilities and programs. Instruments and techniques are developed and shared among the community. The FRIB-TA, a future nuclear astrophysics center that builds on the success of JINA, and Nuclear Data efforts tie the research to the broader goals of our field and are essential components. Investments in these endeavors are necessary to maintain U.S. leadership worldwide in low-energy nuclear science.

OUR FIELD, ITS ACCOMPLISHMENTS, VISION, AND SYNERGIES IN A NUTSHELL

NUCLEAR STRUCTURE AND REACTIONS

The field of low-energy nuclear structure and reactions is at the brink of a new age of discovery with FRIB operational and ramping up beam power, ATLAS' multi-user upgrade and extension of experimental capabilities, the vibrant activities at the ARUNA laboratories, and staggering advances in nuclear theory for the modeling of the nuclear many-body system and its reactions. We also see tremendous opportunity in the coming decade from leveraging advanced high-performance computing and emerging AI, ML, and quantum information science and technologies.

The overarching goal of research in nuclear structure and reactions is to arrive at a predictive understanding of the underlying nature of atomic nuclei, the limits to their existence, and their behavior in nuclear decays and reactions. This entails a concerted experimental, theoretical, and computational effort spanning the entire chart of nuclides (the two-dimensional landscape organizing isotopes as a function of their number of neutrons, N , and protons, Z , collectively known as nucleons).

Atomic nuclei are complex quantum-mechanical systems consisting of tens, or even hundreds, of nucleons. Their binding, dynamics and rich phenomena are governed by the nuclear force, which arises out of the non-perturbative nature of quantum chromodynamics (QCD) at nuclear scales. Effective field theories (EFTs) provide a framework for grounding the properties of nuclei and their dynamics in QCD. Several EFTs have been and will be developed to describe nuclear interactions and phenomena, providing a model-independent means to bridge and benchmark many-body methods across different energy and momentum scales, and rigorously estimate uncertainties. A challenge for the forthcoming decade is to make further progress on Lattice QCD constraints on the parameters of nuclear forces and operators, thus opening the way to predictions even more firmly anchored in the fundamental theory. It is also crucial to continue developing statistical inference strategies to improve more phenomenological estimations of the nuclear force parameters and quantify theoretical uncertainties in predictions of nuclear observables, especially where experimental data are scarce or nonexistent.

Which combinations of protons and neutrons can be bound together to form a nucleus? This intriguing and yet basic question is at the heart of low-energy nuclear physics. It motivates the exploration of the limits of the nuclear landscape and provides stringent tests of our understanding of the nuclear force and atomic nuclei. The nuclear chart is bordered in the east and west by the nucleon driplines, where the addition of neutrons and protons, respectively, no longer yields bound systems. At the northern border, defining the limits of discovery of superheavy

nuclei, the strong force can no longer overcome the electrostatic repulsion of protons within the nucleus. Since the last LRP, global, microscopic predictions not only of nuclear binding, but also of beta decay rates, fission product yields, proton radioactivity rates, etc., with quantified uncertainties have become available across the entire chart of isotopes and await to be tested against experimental data. The neutron dripline has been firmly established up to $Z = 10$, i.e., for the neon isotopes, and perhaps for the sodium isotopes ($Z = 11$). A variety of systems beyond the proton dripline were discovered, with the four and five proton emitters ${}^9\text{N}$ and ${}^{18}\text{Mg}$ characterized at NSCL being the most exotic ones. Experiments at the ATLAS facility solved the puzzles of the ${}^{185}\text{Bi}$ decay, the heaviest known proton emitter. In superheavy territory, four new elements were added to the periodic table ($Z = 113, 115, 117$, and 118) at facilities abroad, with critical US participation and using targets produced at ORNL, while the first direct determination of the mass number, A , of a superheavy element was made at LBNL using a novel type of spectrometer. The future of the quest for the limits of the nuclear landscape is bright. FRIB is the only facility that will have the beam power to reach beyond magnesium and establish the neutron dripline up to zinc ($Z = 30$). A unique opportunity is afforded by the FRIB400 energy upgrade, which would open the way to charting most of the neutron dripline up to neodymium ($Z = 60$). If it exists, even the neutron-laden $N = 50$ isotope ${}^{70}\text{Ca}$ could be discovered. At the proton dripline, FRIB's high beam intensities will bring into reach heavy two-proton emitters for the first time and enable the study of more than just a handful of decays and their proton-proton correlations. Measurements will also blaze into the region of doubly magic ${}^{100}\text{Sn}$ with the FDS. The long-term prospects in the unexplored regions of mass and charge are fascinating, with a concerted US effort at the horizon to produce element $Z = 120$ at LBNL. Along the way, new opportunities to study isotopes of transfermium elements at ATLAS and to anchor the nuclear models that are needed to extrapolate into superheavy territory emerge thanks to detection-system upgrades. Meanwhile, the microscopic description of nuclear structure across the chart of isotopes will improve in reach and accuracy. Multi-reference approaches and techniques such as tensor networks, combined with new ideas will allow nuclear theory to tackle challenges in the description of nuclei, including capturing many-body correlations in medium-mass and heavy nuclei, and accessing heavy open-shell nuclei. Nuclear density functional (DFT) theories will also enable a consistent, microscopic description of nuclear structure, reactions, and decays in superheavy nuclei. A predictive understanding of the complex phenomenon of nuclear fission in basic science and in nuclear energy applications is now on the horizon.

Near the driplines, the proximity to the energy continuum leads to the emergence of new phenomena characteristic of open quantum systems, i.e., systems coupled to an external environment (in this case, the continuum of scattering and reactions). This regime gives rise to exotic forms of radioactivity, and challenges our assumptions about nuclear sizes, nucleonic shells, and other nuclear properties. A new frontier for the upcoming decade will be the development of a unified description of structure and dynamics required to arrive at a more fundamental understanding of threshold phenomena and the structure and low-energy spectra of these dripline systems. Significant steps in this direction have already been taken in the past decade, with the incorporation of the particle continuum in structure calculations and the unification of structure and reaction theory for lighter nuclei. Emergent phenomena such as alpha clustering and the scattering behavior of weakly-bound systems are now starting to directly come out of *ab initio* computations. One of the many highlights since the last LRP is the observation of beta-delayed proton emission following the decay of ${}^{11}\text{Be}$. To explain the observations, a near-threshold state in ${}^{11}\text{B}$ was postulated through which such a unique decay could proceed and it was later found and characterized. Understanding this phenomenon took three experiments performed at an international facility, TRIUMF (Canada), at the National Superconducting Cyclotron Laboratory (NSCL), and at Florida State University (FSU), an ARUNA facility. Unexpected phenomena, such as a tetra-neutron correlation, have been reported. Over the next LRP period, discoveries in this field will come into the reach of FRIB. This will place exotic, weakly-bound, or unbound nuclei

under the experimental and theoretical microscope and exposing unusual properties that will teach us unique lessons in the quest to understand and model nuclei.

Nuclear science is fortunate that one of the key drivers of structural change presents a lever, of sorts. Nuclei can be studied along chains of isotopes so that the proton number remains constant while the neutron number, and hence the isospin, changes along the chain. This allows us to study how the large neutron-to-proton asymmetry drives structural change in rare isotopes. Conquering nuclear structure along an isotopic chain, ATLAS and ARUNA facilities have critical roles in tracking the properties near stability, bridging the gap towards the very neutron-rich systems only within reach at FRIB. This full picture of nuclear structure physics is needed to develop and refine models of nuclei and their reactions. In the past seven years, *ab initio* nuclear many-body calculations have made great strides and managed to blaze beyond closed shells and light nuclei, enabling quantified predictions along isotopic chains and reaching systems as heavy as ^{208}Pb , with great promise for the future. While the chain of oxygen isotopes has been the textbook case until now, the Ca, Ni, and Sn isotopes will become the systems of choice now that experiment and theory have caught up in reaching these systems. ANL's nuCARIBU facility will provide opportunities in the region around doubly-magic ^{132}Sn . For the Ni isotopes, for example, FRIB400 will bring within reach ^{84}Ni and ^{86}Ni for experiments at the HRS. These systems are predicted to have exceptionally thick neutron skins, something never encountered so far. A successful concept in nuclear science has been the shell model, where the idea of changing magic numbers with N/Z ratio has been a hallmark of the study of rare isotopes. The recent past has seen the pioneering studies of nuclei in the ^{54}Ca region and of ^{78}Ni at facilities abroad. Great strides have been made in characterizing the N=28 and N=40 islands of inversion, where much has been learned about the drivers of shell evolution. With GRETA & HRS and the FDS at FRIB, pioneering spectroscopy of ^{60}Ca can be performed, while FRIB400 is needed to reach beyond and approach N=50 in the key Cr and Fe chains. The N=126 Factory at ANL will open the way to the study of the neutron-rich nuclei below doubly-magic ^{208}Pb for shell-evolution studies. Predictions of extreme neutron skins exceeding 0.5 fm, and the potential loss of electron and nucleon shell structures for superheavy elements let us anticipate an acceleration of discovery science taking full advantage of the increased opportunities awaiting us in the future.

Excited states in nuclei often display the emergence of collective phenomena, resulting in deformation and the coexistence of different shapes within a small window of energy. How such phenomena evolve towards the limits of existence is an open question. Since the last Long Range Plan, the elusive phenomenon of triaxial nuclear shapes was explored in measurements at CARIBU at ATLAS and at ReA at NSCL, while high-lying excitation modes in stable nuclei were explored at the unique HIγS facility. The latter facility was also instrumental in exploring shape coexistence at high excitation energy, but low spin. Octupole collectivity, which in certain regions is predicted to have considerable impact on atomic electric dipole moment (EDM) measurements, was explored at CARIBU at ATLAS. In the future, these measurements will be transformed by the availability of GRETA for experiments at ANL, and by the availability of unique octupole deformed nuclei from fragmentation of uranium beams at FRIB. *Ab initio* approaches have made substantial progress in the past decade and offer the possibility to directly link forces governed by QCD to ordered patterns in nuclear structure and collective modes. *Ab initio* many-body calculations that start from deformed configurations, effective field theories, and symmetry-adapted many-body techniques, and time-dependent DFT methods and other beyond-mean-field techniques have begun to describe collectivity and deformation in novel ways, whereas reaching heavy nuclei remains a challenge and opportunity for the future.

The nuclear equation of state (EOS) connects the temperature, pressure, and density of a nuclear system and governs nuclei and neutron stars. A critical dimension for exploration is the density dependence of the symmetry energy which can be accomplished by compressing nuclear matter in heavy ion collisions. In the US, lower density

observables have been characterized with reaction experiments at TAMU, and the super-saturation density regime has been tackled at NSCL and RIB (Japan). Laboratory constraints have been obtained to almost twice saturation density, albeit with large uncertainties. Together with neutron-star merger observations, the HRS at FRIB will allow reducing the uncertainties in the high-density regime, adding points at large isospin, while FRIB400 is needed to reach twice saturation density, the important milestone for understanding the matter in neutron stars. This wealth of new data will challenge nuclear theory to develop nuclear forces that, when used as input to *ab initio* calculations, accurately describe observables in few-nucleon systems, the properties of medium-mass nuclei, and the saturation of infinite nuclear matter simultaneously. This represents an opportunity for the community to develop a deeper and more quantitative understanding of the connection between properties of matter and finite nuclei. Other opportunities for nuclear theory are in the advancement of models which are needed to connect heavy-ion collisions with the nuclear equation of state and ultimately neutron stars.

Aside from being many-body dynamic phenomena fully deserving of dedicated exploration, nuclear reactions connect experimental observables obtained at accelerated-beam facilities with specific aspects of nuclear structure and are essential for a variety of applications in nuclear astrophysics, nuclear energy, medicine, security, and industry. They span energies from the Coulomb barrier to hundreds of MeV/nucleon, probing many aspects of nuclei. *Ab-initio* descriptions of reactions have made tremendous progress in the last decade. Thermonuclear reactions between light nuclei during the Big Bang, in the interior of the Sun, and in terrestrial fusion experiments can now be computed without any uncontrolled approximations, and extensions to heavier targets and projectiles will enable quantified predictions of helium burning and other stellar nucleosynthetic processes. For reactions involving medium-mass and heavy nuclei, descriptions in terms of a few active degrees of freedom have advanced to provide insight into the dynamics of complex and exotic processes, such as two-nucleon emission and three-body breakup as well as (p,2p) and (p,pn) reactions. Further developments of effective three- (or higher-) body treatment of direct reactions with two-nucleon halos and other exotic nuclei will be needed as FRIB charts the driplines. Another exciting opportunity for improving the description of both direct and statistical reaction calculations lies in the development of nucleon-nucleus effective interactions rooted in *ab-initio* nuclear structure and based on controlled approximations. Realistic simulations of heavy-ion collisions are now possible and may open new avenues to predict fusion cross sections of superheavy elements. Fission theory has made major strides in ever-accurate predictions of spontaneous fission half-lives, fission product yields, and the fission spectrum. Advances in time-dependent density functional theory will open new opportunities, not only for the description of fission or heavy-ion collisions, but also to describe the emergence of pasta phases and modes in the neutron star crust. Recent experimental advances include a renaissance of (p,2p) reactions for rare isotopes at GSI/FAIR (Germany) and RIBF (Japan) and transfer reactions at the extreme values of isospin. The future will see opportunities to perform precision stable-beam transfer reactions using the Enge split pole spectrometers at FSU, Notre Dame, and TUNL, benchmarking optical potentials and mapping the nuclear resonances with radioactive and stable isotope beams at ARUNA facilities. New and more intense rare-isotope beams for reaction studies at nuCARIBU at ATLAS and ReA at FRIB will open new avenues of exploration, particularly once ReA energies exceed 10 MeV/u and a large acceptance spectrometer ISLA is available for high-intensity beams. The HRS will become the workhorse device for fast-beam reactions and inverse-kinematics fission studies at FRIB. Only with the high beam energies provided with FRIB400, however, (p,2p) reactions will become reasonably feasible while also improving frequently used, powerful approximations in reaction models for fast-beam experiments.

NUCLEAR ASTROPHYSICS

The field of nuclear astrophysics seeks to understand the nuclear and neutrino physics that is at the heart of astrophysical processes in our galaxy and the universe as a whole. Its broad scope covers questions such as: What

are the astrophysical origins of the chemical elements? How do stars evolve, and what signatures do they leave behind? What is the nature of nuclear matter under extreme conditions? A confluence of breakthroughs in multi-messenger astronomy, laboratory nuclear physics, and computational modeling of nuclei and the extreme astrophysical environments where they react, has propelled nuclear astrophysics to the forefront of science. These breakthroughs provide extraordinary opportunities for nuclear science – working together with astronomers, geochemists, and experts in other fields – to address long-standing fundamental questions about the cosmos.

The first gravitational wave observations from compact object mergers represent an incredible advance in observational astronomy and have led directly to improvements in our understanding of nuclear matter. New detectors for cosmic neutrinos, an upcoming MeV-scale gamma-ray mission, new X-ray telescopes, new optical telescopes with unprecedented time domain coverage, new capabilities to analyze stardust, and the advent of asteroseismology are likely to bring similar advances for nuclear astrophysics. Nuclear physics plays an essential role in the extreme astrophysical environments encountered in the majority of targets for this new era of multi-messenger astronomy. Indeed, one of the main motivations for next generation, high frequency gravitational wave observatories is the nuclear physics of neutron stars. A different kind of messenger that drives an increased need for nuclear physics is stellar spectroscopy. While stellar spectroscopy has a long history, efforts are now reaching a scale where a detailed map of the evolution of the elemental composition of the Galaxy over its entire history is emerging. Analysis of this “fossil record” of chemical evolution is revolutionizing nuclear astrophysics, pointing to a new, unanticipated diversity of nucleosynthetic processes.

In parallel, advances in experimental nuclear physics are poised to address the dramatically increased need to understand the underlying nuclear physics of stars, stellar explosions, and element synthesis. These advances include a new generation of revolutionary rare isotope beam facilities, in particular FRIB and the forthcoming novel beam production upgrades at ATLAS, underground accelerator laboratories, and a whole suite of major developments at a broad range of above-ground accelerator facilities and ARUNA laboratories providing charged particle, gamma, and neutron beams. This creates unprecedented opportunities to address long-standing nuclear physics challenges in astrophysics: to study the properties and reactions of unstable nuclei made in stellar explosions, to understand the physics of nuclear reactions at extremely low energies and cross sections, and to probe nuclear physics at extreme densities in the laboratory.

Simultaneously, the rise of Exascale computational facilities, and support for the development of nuclear astrophysics codes that can take advantage of them, are beginning to enable computational modeling of astrophysical environments that achieve sufficient fidelity to adequately include the key nuclear processes. This is especially true for the many multi-messenger sites where three-dimensional simulations have turned out to be essential, such as neutron star mergers or supernovae. These simulations are key to understanding the origin of the elements, elucidating the nuclear reactions that govern these events, and providing the essential link between nuclear physics and the astronomical observables. In parallel, Exascale computations of nuclear structure and nuclear reactions that remain inaccessible to experiment are providing missing data for these simulations.

The synergy of these developments in nuclear physics, astronomy, and computing put nuclear science and nuclear astrophysics at a special point in time, with a new understanding of the nuclear processes that shape the visible universe within our grasp. In order to take advantage of this opportunity, full support of the extraordinarily broad range of required technical capabilities and developments in experiment, theory, and computational modeling is essential. This requires supporting the correspondingly broad range of research groups at national laboratories, user facilities, and universities needed to address this multi-physics challenge. Research centers will play an important role in creating the connections between these different areas. Of particular importance for nuclear astrophysics

will be interdisciplinary centers and networks that span nuclear experiment, nuclear theory, computational physics, astrophysics, astronomical observations, and cosmochemistry to facilitate and drive national and international collaborations, the timely exchange of ideas and data, and build the interdisciplinary communities for the multi-messenger era in nuclear astrophysics.

Understanding the synthesis of the elements, primarily those with atomic numbers greater than iron, remains one of the biggest open questions in nuclear astrophysics. Over the last decade, as fidelity has improved in nuclear data, astrophysical simulations, and the observational constraints, it has become clear that there are multiple, distinct nucleosynthetic processes contributing to their formation. The heaviest elements form via rapid neutron capture, and the dramatic recent multi-messenger observations of the neutron star merger gravitational wave event, GW170817, marked the first direct observation of a site of this process. The ability to accurately model the r-process-powered light curve of this kilonova was a triumph for the field and has triggered unprecedented progress in computational modeling of these events. There is now an opportunity to combine gravitational wave-triggered kilonova observations with new rare isotope physics from experiment and theory, new equation of state physics, new neutrino physics, high fidelity end-to-end computer models, and stellar spectroscopy data to quantify the contribution of neutron star mergers to the tally of galactic heavy element abundances for the first time.

This decade saw increasing evidence for a myriad of neutron and proton capture processes operating in our Galaxy. This evidence was provided by a combination of laboratory measurements of neutron-generating and neutron-capture reactions; advances in modeling of stars to explore the three-dimensional nature of these shells; laboratory analysis of stardust; and a dramatic increase in stellar spectroscopy data. Together, these environments require a much broader, more complex, and more robust set of nuclear data, including lifetimes and masses, neutron-induced reaction rates on stable and unstable isotopes from stability to the neutron drip line, photo-disintegration reaction rates, alpha- and proton-induced reactions rates on heavy, unstable and stable isotopes, fission probabilities and products, and information on nuclear isomers. With the FRIB facility, the proposed FRIB400 upgrades, and the upcoming N=126 Factory and nuCARIBU upgrades at ANL, there is now a tremendous opportunity to address the wide range of nuclear physics inputs needed to understand the new diversity of astrophysical environments that appear to contribute to the heavy-element nucleosynthesis puzzle. Another critical capability is the nuclear structure and reaction theory used to turn direct and indirect measurements into evaluated nuclear data and to predict nuclear properties that cannot be measured. Anticipated advances in theory will result in better predictive power and, therefore, provide benefits to nuclear astrophysics simulations.

New successful measurements of key nuclear reactions in stars, in combination with progress in reaction theory and stellar models, had very broad impacts on the field. This includes understanding the onset of nucleosynthesis in the first stars, which is revealed in the present day by observations of the composition of the oldest surviving stars in the Galaxy. It includes an expanded understanding of the interior of the Sun through improved measurements of the reactions in the CNO cycle, in combination with the first detection of solar neutrinos from this cycle. The fundamental challenge for nuclear physics is to determine nuclear reaction rates at extremely low energies near the reaction threshold, where impressive progress has been made over the past decade. Advances in available facilities, instruments, and techniques have enabled measurements at extremely low energies as well as high-precision measurements at higher energies. Further progress in direct measurements at low energies at underground facilities, such as CASPAR, and high current above-ground facilities, such as LENA-II and Sta. Ana, coupled with experimental and theoretical advances in indirect methods are critical for guiding extrapolations into the astrophysical energy regime. With recent investments in nuclear facilities and devices at FRIB, ATLAS at ANL, and the ARUNA laboratories, we are well positioned to seize on opportunities to address long-standing fundamental open

questions about stellar reaction rates at very low energies. Anticipating these advances combined with new observational windows into stars enabled by the JWST, there is now a major opportunity for theory to advance multidimensional stellar models along the entire stellar evolution sequence.

Advances in laboratory measurements of stable and radioactive beam reactions, in combination with advances in computational modeling, have also led to tremendous progress in understanding other nuclear-powered stellar explosions. A sustained effort at a diverse range of stable and radioactive beam facilities has made classical novae the first astrophysical site where the majority of nuclear reactions are informed by direct measurements at the relevant astrophysical energies. A broader effort, again combining radioactive beam and stable beam accelerator facilities, has now addressed some of the key nuclear physics related to neutron deficient unstable nuclei in the rp-process that powers X-ray bursts. After decades of effort, modeling of core-collapse supernovae now qualitatively reproduces the basic observations of the explosion energy and ejected mass of radioactive nickel. This progress has relied on three-dimensional modeling, utilizing world-class computing resources, as well as better understanding of the nuclear equation of state and the weak nuclear reactions that drive the collapse of the stellar core. Simulations of thermonuclear supernovae, challenged by observations, have made tremendous progress on reconciling progenitor scenarios and observable outcomes. Surveys like that planned with the Vera Rubin Telescope will reveal time-dependent astrophysical scenarios in prodigious numbers due to their unprecedented sky and time coverage. In the coming decade, we will be able to understand the electromagnetic, nucleosynthetic, radioactive, and stardust fingerprints of a broad range of transients such as novae, supernovae, X-ray bursts, kilonovae, cooling neutron stars, as well as potentially novel, hitherto undiscovered, types of transients. This understanding will be enabled by a combination of novel instrumentation and facilities to measure nuclear reactions on stable and unstable nuclei and significantly advanced computational models of astrophysical sites.

Unprecedented progress has also been achieved in the understanding of the dense matter equation of state that governs the properties of neutron stars. While laboratory heavy-ion collision experiments have provided much-refined constraints, these have now been complemented with an expanded range of additional new constraints: gravitational wave signals from neutron star mergers, effective field theory with uncertainty quantification, and observations of X-ray pulsar light curves with the ISS-based NICER observatory. As a consequence, significant progress has been made in constraining the nuclear matter equation of state, including the symmetry energy, particularly below and near saturation density. Going beyond that to cover and better constrain the entire density range of importance for nuclear astrophysics will be a challenge for the future. More precise measurements for symmetric matter are necessary and within reach, as are stronger symmetry energy constraints. Heavy-ion collision observables, such as particle yield ratios, the flow patterns of particles, and collective excitations of nuclei, must be compared to theoretical predictions, such as those from dynamical transport simulations of heavy ion collisions, to extract equation-of-state parameters. These require measurements at existing facilities (including RHIC beam energy scan), facility upgrades (including FRIB400, HRS, N=126 factory), detector investments, transport model improvements, support for ARUNA labs, and continued investment in the training of young scientists. The value of such investments is multiplied when coupled to astronomical observations, such as the properties of neutron stars and the signatures of neutron star mergers. The dynamics of such mergers affect the ejection of neutron star material for nucleosynthesis and the fate of the post-merger object. The new ability to observe gravitational waves from neutron star mergers, as well as the light emitted during and after the merger using precision terrestrial measurements, has opened a new synergy between nuclear science and astronomy that is rapidly increasing our understanding in both fields.

FACILITIES

To achieve its full discovery potential through a robust research program, the field requires the continued upgrade of its facilities and instruments. At the present time, FRIB is carrying out first experiments with world-class equipment developed with large community involvement. At the same time, the ATLAS facility continues to serve a large number of users while upgrading its capabilities to meet demand. ARUNA facilities complement these two user facilities while often providing unique additional capabilities (types of beams, beam time, detectors). The community continues to upgrade its existing detectors while also developing first rate instrumentation and new concepts to further expand the reach of the science. However, to reach its full potential the field requires a number of modest investments. These all represent opportunities for development of the next generation of nuclear scientists for the benefit of society. With these provisions, the future is bright.

SYNERGIES AND BROADER IMPACT

Advances in computation are both synergistic and with broader impact. The ever-increasing computational power over the last decade has accelerated scientific discovery and transformed the field of low-energy nuclear physics and astrophysics. We are now entering a new and exciting era where we will see significant improvements in the simulation capabilities of atomic nuclei and their behavior in decays and reactions, nuclear matter, and interactions with neutrinos and electrons, and stellar explosions. These results will be relevant to many applications in nuclear energy, nuclear security, medicine, and nuclear astrophysics. We will be able to provide predictions for key nuclei relevant to ATLAS, FRIB and other experimental activities worldwide, and guide state-of-the-art updates to evaluated nuclear data libraries. New technologies have also given rise to entirely new paradigms for computing that were not available a decade ago. With AI and ML, new algorithms are being used to learn about correlations and patterns in data, accelerate calculations, make predictions with reliable error estimates, and automate machine operations. The rapid progress in these areas has been fueled by interdisciplinary collaborations between physicists, computer scientists, statisticians, and applied mathematicians. These collaborations—and mechanisms that support them—are essential to continued innovation in HPC, uncertainty quantification, AI, and ML for nuclear physics. Interdisciplinary collaboration is similarly crucial to progress in QC. The large information capacity of qubits and their inherent quantum mechanical nature hold the potential for addressing long-unsolved challenges in our understanding of large and strongly entangled quantum systems. But, to realize this potential, nuclear physicists will have to work across sub-fields of physics, and across scientific disciplines.

Nuclear science makes direct and major contributions to solving societal problems and improving the US economy. These contributions include sensitive new tools to detect environmental hazards, such as PFAS contaminants in food products and everyday items, and the testing of critical electronics for space-based applications. The technology and techniques of nuclear science advance nuclear medicine toward diagnoses and cures for a wide range of diseases and help us determine how to respond to nuclear threats and to the spread of nuclear materials. Equally important, the related accelerator science effort is a multi-hundred-billion-dollar enterprise at the core of many industries in the U.S., central to the health industry and to future efforts to meet our national energy needs in an environmentally sound way. Moreover, the field of nuclear science provides the pipeline to our core expertise in nuclear detector technologies, data analysis and data science techniques, accelerator science, and cryogenic engineering. This highly trained workforce helps ensure continued growth in both U.S. industry and medicine.

The field is acutely aware of the essential role nuclear data plays in all facets of nuclear science. A critical issue is to maintain a high level of expertise in nuclear data evaluation to ensure sufficient breadth and quality of the nuclear

databases and to meet the requirements of a continuously developing user community – impacting nuclear structure and reactions physics, nuclear astrophysics, fundamental symmetries, and applications of nuclear science. The availability of credible and reliable nuclear data libraries provides a bridge between science, technology, and society by making the results of basic nuclear physics research available to a broad audience of users. Investments in the US nuclear data efforts and the corresponding workforce can leverage the discoveries awaiting us to impact other related fields and society.

The connection between nuclear structure and reactions and tests of the fundamental symmetries of nature has historically played a major role in nuclear science, from characterizing the necessary dynamics and properties of the nuclear force to discovering the violation of parity symmetry in nuclear beta decay. More recently, the interface between these two communities has focused on trying to understand the unusual properties of neutrinos, searching for new violations of basic symmetries in subatomic forces, and performing precision tests of the present Standard Model of the strong, weak, and electromagnetic forces. Nuclear structure theory has made great progress in evaluating the matrix elements necessary to interpret neutrino-less double beta decay experiments, and more work is needed in the next decade to arrive at quantitative predictions. Experiments have begun to explore many nuclear structure properties of candidate nuclei for neutrino-less double beta decay. Enormous opportunities exist for the field of nuclear structure physics during the upcoming Long Range Plan period, through the experimental and theoretical characterization of pear-shaped candidate nuclei for atomic EDM (electric dipole moment) searches for which octupole deformation is predicted to be a many-orders-of-magnitude enhancer. For the atomic or molecular EDM measurements and preparatory experiments themselves, candidate nuclei not available elsewhere can be harvested at FRIB.

An intellectual intersection exists with the Jefferson Laboratory nuclear structure program where the PREX and CREX measurements have benefitted from countless nuclear theory calculations as to the results' consistency and impact on the nuclear equation of state and related observables. In particular, the connection of the Jefferson Laboratory studies of NN short-range correlations to our understanding of the nuclear force remains an ongoing research topic at the intersection of our fields.

Quantitative and qualitative understanding of strongly correlated fermionic systems is at the heart of nuclear physics, but this problem is also ubiquitous in quantum chemistry, ultracold atomic gases, and condensed matter. Nuclear theory has been at the forefront of progress in this multidisciplinary area and continues to benefit from developments in other fields of physics. Nuclear theory is also benefiting from and contributing to advances in quantum information science. The development of quantum algorithms to solve the many-body problem could lead to a dramatic acceleration of the field, and studies of entanglement measures in nuclei could provide new insights and novel ways to address the problem. The next decade will also see the beginning of attempts to simulate real-time quantum dynamics of strongly interacting matter on quantum hardware. Weakly bound and unbound nuclei are open quantum systems presenting generic features also found in atoms, molecules, quantum dots, quantum optics devices, etc. Open quantum systems offer many crucial insights into fundamental problems of quantum mechanics related to irreversibility and decay, measurement of the collapse of the wave function, and the role of entanglement in the dynamics of quantum systems.

The nuclear science community requires nuclides of specific chemical and isotopic purity to explore the bounds of the periodic table, study nuclear structure, and meet the nuclear data needs for applications. There is a strong synergy and overlap in interest and expertise between the DOE-funded Isotope and Nuclear Physics programs. The existing radioisotope production capabilities at LANL's Isotope Production Facility (IPF), the Brookhaven Linac Isotope Producer (BLIP), and ORNL's High Flux Isotope Reactor (HFIR) will soon be augmented by isotope harvesting

at FRIB, which has the potential to become a novel source of radionuclides. The University Isotope Network, funded by DOE's Isotope Program, was created to leverage and coordinate the nationally distributed collection of university-based accelerators to produce radionuclides and facilitate technological developments. New technologies to enable experiments that involve radionuclides will be essential. Research efforts are required to develop new and to improve existing technologies for producing radioactive targets (including actinide targets), and to identify the best route to make the desired isotopes with high yield and radio-purity. Innovative ideas, such as the notion of using fast-neutron activation at the National Ignition Facility or exploiting neutron interactions with radionuclides (or rare stable isotopes) in inverse kinematics, are interesting concepts to explore. There is a new opportunity for cooperation between the nuclear science community in the US and European colleagues. The European Rare Stable Isotope Supply (EURASIS) initiative started recently in response to the supply shortage of enriched stable isotopes (ESI) may serve as a platform for promoting a concerted effort of research communities in the US and Europe. Radionuclide science requires collaboration across isotope production, radiochemical separation, target fabrication, nuclear physics, and other fields. Therefore, skills in many areas of study are required, and workforce development efforts, such as DOE-funded Horizon-broadening Isotope Production Pipeline Opportunities (HIPPO) program, are important components of the national isotope program.

It is crucial for the health of the nuclear science community and our service to the nation to educate young people and the public in nuclear science and to grow the nuclear science workforce. There are a number of independent dynamic programs working on these important endeavors at institutions across the country. It is important that the community supports and shares information and best practices to promote education, workforce development, and public engagement. The ability to attract, grow and sustain a national nuclear workforce depends on our community's commitment to diversity, equity, inclusion, and belonging. It is essential that institutions and workplaces are supportive, diverse, and inclusive, naturally promoting inquisitiveness, intellectual curiosity, and engagement. Initiatives such as the DNP Allies, codes of conduct, and community agreements are endorsed as means to hold community members and our institutions accountable. As a nuclear science community and as individuals within this community, we assert our commitment to creating environments free from harassment where all people can succeed.

FULL TEXT OF THE RESOLUTIONS

PREAMBLE

Nuclear science is at a unique moment: experimental facilities and astronomical observatories promise a wealth of data in the next decade, while advances in theory and computing, together with emerging artificial intelligence, machine learning, and quantum computing technologies provide unprecedented opportunities for fundamental discoveries with broad implications throughout physics and astrophysics. The low-energy nuclear science community is developing a predictive understanding of atomic nuclei and their interactions; elucidating the chemical history of the Universe; revealing the fingerprints of nuclear structure, decays, and reactions in astrophysical processes; using atomic nuclei as laboratories to test nature's fundamental symmetries; and providing accredited data, tools, and related technologies to advance important societal applications of nuclear science. Investments in national user and university-based facilities delivering beams of stable and rare isotopes, state-of-the-art instrumentation, and initiatives have laid the foundation for the scientific output of our field for the next decade. A healthy and robust research program, upgrades and new instruments, and the development and retention of a diverse and equitable workforce are now needed to capitalize on these investments and accelerate progress toward achieving the broad science goals of our community.

AFFIRMATION

Our community affirms in the strongest possible terms its commitment to foster a diverse and equitable workforce and to support and respect diversity in all its forms. Individually and collectively, we commit to ensuring an inclusive and accessible environment for all and taking action if these values are not being upheld.

RESOLUTION 1

The highest priority for low-energy nuclear physics and nuclear astrophysics research is to maintain U.S. world leadership in nuclear science by capitalizing on recent investments. To this end, we strongly support:

- Robust theoretical and experimental research programs and the development and retention of a diverse and equitable workforce;
- The optimal operation of the FRIB and ATLAS national user facilities;
- Investments in the ARUNA facilities, and key national laboratory facilities;
- The FRIB Theory Alliance and all its initiatives.

All are critical to fully realize the scientific potential of the field and foster future breakthroughs.

RESOLUTION 2

The science case for an energy upgrade of FRIB to 400 MeV/u is compelling. FRIB400 greatly expands the opportunities in the field. We strongly endorse starting the upgrade during the upcoming Long Range Plan period to harness its significant discovery potential. We support instrument developments, including the FDS and ISLA now that GRETA and HRS are underway. These community devices are important to realize the full scope of scientific opportunities.

RESOLUTION 3

Computing is essential to advance all fields of nuclear science. We strongly support enhancing opportunities in computational nuclear science to accelerate discoveries and maintain U.S. leadership by:

- Strengthening programs and partnerships to ensure the efficient utilization of new high-performance computing (HPC) hardware and new capabilities and approaches offered by artificial intelligence/machine learning (AI/ML) and quantum computing (QC);
- Establishing programs that support the education, training of, and professional pathways for a diverse and multidisciplinary workforce with cross-disciplinary collaborations in HPC, AI/ML, and QC;
- Expanding access to dedicated hardware and resources for HPC and new emerging computational technologies, as well as capacity computing essential for many research efforts.

RESOLUTION 4

Research centers are important for low-energy nuclear science. They facilitate strong national and international communications and collaborations across disciplines and across theory and experiment. Interdisciplinary centers are particularly essential for nuclear astrophysics to seize new scientific opportunities in this area. We strongly endorse a nuclear astrophysics center that builds on the success of JINA, fulfills this vital role, and propels innovation in the multi-messenger era.

RESOLUTION 5

Nuclear data play an essential role in all facets of nuclear science. Access to reliable, complete and up-to-date nuclear structure and reaction data is crucial for the fundamental nuclear physics research enterprise, as well as for the successes of applied missions in the areas of defense and security, nuclear energy, space exploration, isotope production, and medical applications. It is thus imperative to maintain an effective US role in the stewardship of nuclear data.

- We endorse support for the compilation, evaluation, dissemination and preservation of nuclear data and efforts to build a diverse, equitable and inclusive workforce that maintains reliable and up-to-date nuclear databases through national and international partnerships.
- We recommend prioritizing opportunities that enhance the prompt availability and quality of nuclear data and its utility for propelling scientific progress in nuclear structure, reactions and astrophysics and other fundamental physics research programs.
- We endorse identifying interagency-supported crosscutting opportunities for nuclear data with other programs that enrich the utility of nuclear data in both science and society.

CONCLUSION

The low-energy nuclear science community comprises a dynamic and skilled workforce. The members of this community, with diverse educational backgrounds and research interests, assembled at Argonne National Lab during its first snowstorm of the season to discuss exciting science from the past seven years and to look to the future. We agree that a broad research program at a diverse array of institutions is essential to enable discovery in an era when a wealth of new data is expected. The sum of the large- and small-scale facilities, together with overarching theory, computing, and data efforts, and the development and growth of a world-leading, diverse workforce will ensure the vitality of our community. FRIB and its key FRIB400 upgrade will provide access to the extremely neutron-rich isotopes required to build a more complete picture of nuclear matter and its role in the Cosmos. ATLAS provides a complementary suite of beams and tools the research community needs. The ARUNA laboratories offer unique, specialized facilities and research opportunities, while providing outstanding training for the next generation of nuclear scientists. Primarily undergraduate and minority serving institutions are essential pillars for developing a robust and diverse workforce. Key national laboratory facilities contribute targeted capabilities and programs. Instruments and techniques are developed and shared among the community. The FRIB-TA, a future nuclear

astrophysics center that builds on the success of JINA, and Nuclear Data efforts tie the research to the broader goals of our field and are essential components. Investments in these endeavors are necessary to maintain U.S. leadership worldwide in low-energy nuclear science.

1 NUCLEAR STRUCTURE AND REACTIONS THEORY

A DECADE OF UNPRECEDENTED OPPORTUNITY

The coming decade provides us with unprecedented opportunities in nuclear physics: We expect a wealth of data – from rare isotope beam facilities, electron-nucleus scattering, neutrino experiments, gravitational wave detections, and from neutron-star and stellar observations – to constrain and challenge our understanding. Forefront nuclear theory will be needed to make sense of all this information, to interpret and guide experiments, and to reliably predict what cannot yet be measured.

Atomic nuclei are complex quantum-mechanical systems consisting of tens, or even hundreds, of particles. Their dynamics and rich phenomena ultimately emerge from the Standard Model of particle physics. While the underlying theory has a small number of parameters and appears relatively simple, tremendous complexity arises out of its non-perturbative nature at nuclear scales. If we look across the nuclear chart we can find both ordered patterns such as shell structure, rotational bands, or clustering, and seemingly random behavior in energy spectra and reaction cross sections. These emergent features are not manifest in the equations of the Standard Model, but they are what make nuclear physics such a rich and diverse field. This then, is the overarching challenge: to be able to accurately predict the properties of nuclei and their behavior in reactions starting from our fundamental knowledge of Quantum Chromodynamics (QCD) and electroweak interactions (see Figure 1.1).

State-of-the-art nuclear theory estimates that about 7000 isotopes can exist [Erl12]. We currently know only about 3000 of these, mostly around the valley of stability. Rare-isotope-beam facilities such as FRIB are expected to give us access to at least 2000 new isotopes with large neutron-to-proton imbalances. These exotic isotopes highlight key challenges [Ots20] in the theory of nuclear structure and reactions: the description of nuclei as open quantum systems; the unification of nuclear structure and reactions [Joh20,Heb22]; the emergence of new degrees of freedom in complex systems [Baz22]; the connection of nuclear forces to QCD [Epe09,Mac11,Ham20]; the efficient and accurate solution of the strongly correlated fermionic many-body problem that lies at the heart of nuclear physics [Her20]; and the collection and evaluation of nuclear data for technological and basic science applications [Kol22]. These challenging, complex, and interconnected problems will take on renewed importance in the FRIB era. Low-energy nuclear theory also offers stimulating interdisciplinary opportunities for connections to strongly correlated fermionic systems, quantum information science, open quantum systems, statistics, and other fields.

In this chapter we first describe, in Section 1.2, the progress made in the theory of nuclear structure and reactions since the 2015 Long Range Plan. The ultimate goal of nuclear theory is a unified treatment of structure, reactions, the nuclear equation of state, and fission & fusion; progress in each of these areas drives and benefits from advances in the others. Nevertheless, for the purposes of this document Section 1.3 describes the challenges and opportunities associated with the various pieces of this interconnected problem in turn, attempting to point to connections between those pieces along the way. In Section 1.4 we briefly discuss connections to other fields of science before closing in Section 1.5 by articulating what is needed to realize the intellectual gains discussed in the earlier sections.

Physics motivation:

- Nuclear forces rooted in QCD.
- Origin of emergent features in exotic nuclei.
- Electroweak processes at non-zero momentum transfer.
- Nuclei as open quantum systems and the emergence of universality.
- Unification of nuclear structure and reactions.
- Spectroscopic quality across the nuclear chart.
- Time-dependent dynamics of fission and fusion.

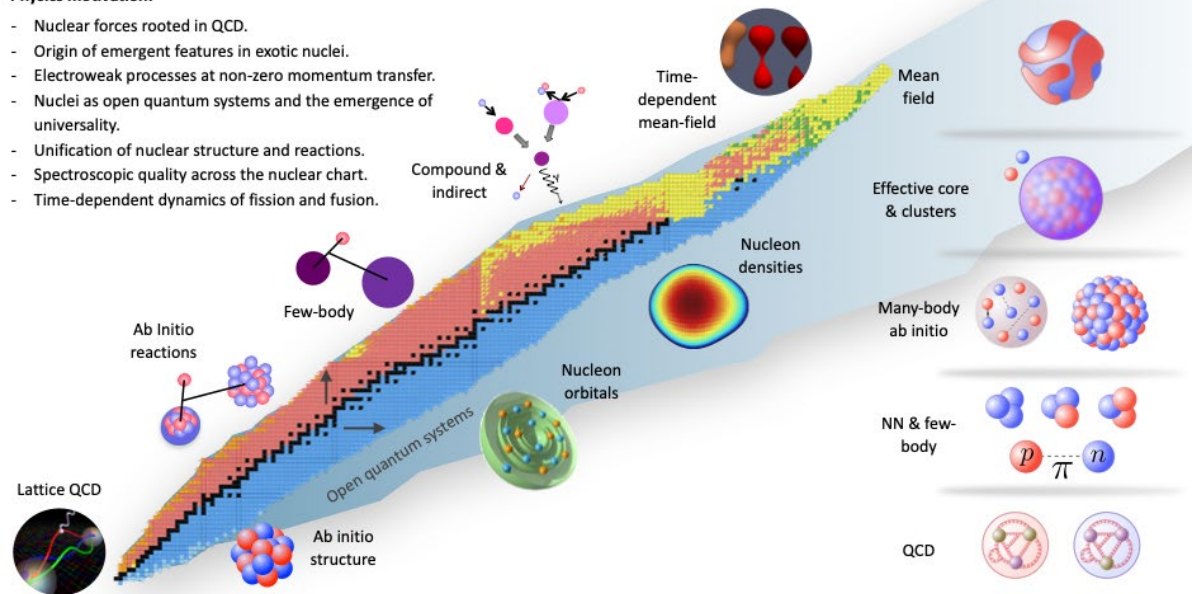


Figure 1.1: Nuclear structure and reaction theory encompasses complementary approaches to enable the predictive description of a broad range of nuclear properties and processes.

PROGRESS SINCE THE LAST LONG RANGE PLAN

The theory of nuclear structure and reactions has made tremendous progress since the last Long Range Plan. It now yields accurate and increasingly precise predictions of critical nuclear observables that include quantified uncertainties, throughout the entire nuclear chart.

Thirty years after Weinberg's seminal papers, chiral effective field theory (EFT) (see [Epe09, Mac11, Ham20] for reviews) is now a standard nuclear-physics tool. Its use, in combination with methods based on Wilson's renormalization group, has revolutionized our understanding of nuclear forces. Nuclear interactions obtained using Chiral EFT are grounded in QCD. They include consistent three-nucleon forces and electroweak currents and are also systematically improvable: they come with estimates of the theoretical uncertainty of calculations that use them.

These forces and operators have then been tested for many light and various closed-shell nuclei using a powerful set of complementary many-body methods [Her20] that exploit ever-increasing forefront computational resources. These tests were made possible by a simultaneous revolution in A -body calculations of atomic nuclei that start from these next-generation nucleon-nucleon and three-nucleon forces. Over the last seven years such *ab initio* calculations – once believed possible only for the lightest nuclei – have advanced from closed-shell isotopes of oxygen, calcium, and nickel to heavy nuclei such as ^{208}Pb , and to medium-mass open-shell nuclei. Phenomena such as alpha-particle clustering in light isotopes and deformation in open-shell nuclei now emerge directly from *ab initio* computations, which have also demonstrated that three-nucleon forces play a pivotal role in nuclear binding, and that two-body currents are essential to an accurate description of magnetic moments, neutrino-nucleus scattering, and beta decays.

Meanwhile, data from rare ion-beam facilities and multi-messenger astrophysics have galvanized progress in the theory of nuclear reactions. *Ab initio* computations that treat the structure and reaction dynamics on equal footing

have advanced to light-ion processes, and optical potentials have been derived from *ab initio* input such as densities and Green's functions. Solution methodologies for three- and four-body quantum-mechanical scattering have been exploited and provide insight into the dynamics of complex and exotic reaction and decay processes, such as two-nucleon emission and three-body breakup as well as (p,2p) & (p,pn) reactions. The description of real-time nuclear dynamics of heavy nuclei at low energies near the Coulomb barrier has made significant progress. Realistic quantum-mechanical simulations of heavy-ion collisions are now possible and may open new avenues to predict fusion cross sections of superheavy elements. Fission theory has made major strides in ever-accurate predictions of spontaneous fission half-lives, fission product yields, and the fission spectrum.

Global, quantum-mechanical predictions of nuclear properties, with quantified uncertainties, have become available across the entire chart of isotopes thanks to simultaneous progress in theoretical methods and advances in leveraging both high-performance computing (HPC), including GPU-accelerated architectures, and machine-learning/artificial-intelligence (ML/AI) techniques. A decade ago, such calculations were largely limited to ground-state atomic masses; now, complex observables such as beta decay rates, fission product yields, proton radioactivity rates, etc., can also be computed within a consistent framework. This progress has, in turn, generated significant advances in predictions of abundance patterns from rapid neutron capture by nuclei (r-process).

Prominent throughout the entire field over the last seven years is the continued leveraging of state-of-the-art leadership-class computing facilities. Since 2015 the use of tools from ML/AI [Boe22] to advance our understanding of nuclear processes and the forces that bind protons and neutrons into nuclei has gone from almost non-existent to routine. Systematically improvable theories, Bayesian methods and model averaging and, more recently, deep learning techniques now allow nuclear theorists to make predictions with quantified uncertainties and to provide reliable, quantitative answers to questions of experimental design.

The FRIB Theory Alliance (FRIB-TA) started in 2015 after ground was broken for the construction of FRIB. It has grown the field and developed talent through its Fellowship and Bridge programs, fostered collaboration on scientific challenges through topical programs and dialogues, and educated the next generation of nuclear scientists through summer schools. To date, the FRIB-TA has launched the careers of eight Fellows and helped create five faculty positions via its Bridge program.

CHALLENGES AND OPPORTUNITIES

1.1.1 FROM NUCLEAR FORCES TO NUCLEAR STRUCTURE...AND BEYOND

Nuclear dynamics is tied to QCD, the theory of the strong force, via a tower of EFTs. EFTs allow practitioners to estimate the uncertainty in their calculation due to the physics they have not considered. They are also model-independent, in the sense that they rest on only very general assumptions about the dynamics and symmetries at work in a system. Several EFTs have been developed to describe nuclear phenomena and interactions. Chiral EFT takes neutrons and protons as its degrees of freedom and is the EFT of strong interactions at energies of order 20-200 MeV [Epe09, Mac11, Ham20].

NUCLEAR FORCES: Many open questions remain in Chiral EFT itself [Fur21]. These are particularly pertinent as we examine multiple observables in a wide variety of nuclei, not all of which are sensitive to the same pieces of the nuclear force. Species near the dripline provide a magnifying glass that focuses attention on otherwise hard to elucidate elements of the fundamental nuclear interaction, such as its isospin dependent terms.

To tie Chiral EFT to QCD requires simulations of the QCD action based on a direct Monte Carlo evaluation of the QCD path integral on a space-time lattice. Nuclear forces based on Chiral EFT come with many undetermined parameters

and lattice QCD techniques can provide helpful constraints on them. However, large uncertainties in lattice QCD calculations of multi-hadron systems presently preclude us from determining all but a few Chiral EFT parameters directly from QCD. A challenge for the forthcoming decade is to make further progress on Lattice QCD constraints on the nuclear force.

In the near-term the parameters of the Chiral EFT nuclear force need to be inferred using experimental data. The resulting parameter-estimation problem is high-dimensional and non-linear. It can also be multi-modal, all of which makes full uncertainty quantification for the nuclear force and propagation of those uncertainties to predictions a computationally intensive problem. It is therefore crucial to continue developing statistical inference strategies to obtain probability distributions, identify sets of observables that capture many important features of nuclear forces and electroweak currents and are within the control of many-body techniques, and quantify theoretical uncertainties in predictions of nuclear observables, especially for those for which experimental data are scarce or nonexistent.

FIRST-PRINCIPLES DESCRIPTION OF NUCLEAR STRUCTURE: Many-body techniques can be benchmarked against each other to estimate systematic uncertainties, while statistical uncertainties can be obtained by building fast and accurate emulators based on, e.g., reduced basis methods, autoencoders, etc. Important challenges remain to, for example, fully capture both static and dynamic correlations in medium-mass and heavy nuclei, access open-shell nuclei away from effective cores, and to handle three-body forces. Multi-reference approaches and new techniques from other areas of theoretical physics, such as tensor networks and factorization schemes, provide novel and perhaps more efficient ways to address high-impact physics questions.

It is a challenge to develop nuclear forces that, when used as input to *ab initio* calculations, accurately describe simultaneously observables in few-nucleon systems, the properties of medium-mass nuclei, and the saturation of infinite nuclear matter [Tew20]. This represents an opportunity for the community to develop a deeper and more quantitative understanding of the connection between properties of matter and finite nuclei. The equation of state of strongly interacting matter is sensitive to features of nuclear dynamics at short distances that impose strong constraints upon the behavior of microscopic Hamiltonians (the nuclear equation of state is discussed in more detail in Section 1.3.3). A better understanding of the formation and characteristics of these correlations in nuclei will shed light on both the role of QCD in nuclei and the physics of high-density strongly interacting matter.

PROBING BEYOND THE STANDARD MODEL AND ELECTROWEAK PHYSICS IN NUCLEI: The observation of neutrinoless double beta decay or a nuclear electric dipole moment within the next decade would demonstrate there is physics Beyond the Standard Model (BSM). Interpretation of such an observation depends on the accurate computation of the relevant nuclear matrix elements. This requires work at widely separated energy scales, from the scale of the BSM physics itself at or above 1 TeV, all the way down to nuclear energies that may be as small as 10 eV in ^{229}Th . EFT provides a connected set of bridges between these scales. The Standard Model EFT (SM EFT) is matched to chiral perturbation theory, with input from Lattice QCD. Chiral-perturbation-theory operators are then used to derive Chiral EFT operators that involve only nucleons and no pions and can thus be used in many-body calculations of nuclei. To realize the full potential of experiments that probe physics beyond the standard model in nuclei therefore requires an interconnected set of calculations, involving knowledge of BSM physics, lattice QCD, Chiral EFT, and nuclear many-body methods, as well as the ability to quantify the uncertainties inherent in each step [Cir22].

There is also a significant opportunity for the nuclear theory community to provide calculations that are essential components of programs at DUNE, FermiLab, and other experiments seeking to determine fundamental neutrino

properties such as masses, mixings, and charge-conjugation parity violation. To do this we will have to understand the dynamics of nuclei at these energy and momentum scales, which means employing accurate nuclear forces and their associated electroweak currents. It is also necessary to extend *ab initio* frameworks to the nuclei relevant to the accelerator-neutrino program, e.g., ^{40}Ar , and keep working on ways to accurately calculate exclusive-channel observables in electron and neutrino scattering.

Electron and neutrino scattering are stringent probes of nuclear dynamics at scales from the size of the nucleus (electroweak form factors) to the average nucleon-nucleon distance and below (quasielastic scattering) [Roc20]. In the next decade nuclear theory can continue to confront rapidly growing data sets from JLab, neutrino facilities, and other laboratories.

EMERGENT FEATURES: Emergence of regular patterns in complex many-body systems, such as atomic nuclei, from the fundamental constituents and the interactions between them is a key problem in many fields of science. *Ab initio* approaches have made substantial progress in the past decade and offer the possibility to directly link forces governed by the QCD to ordered patterns in nuclear structure and dynamics such as collective modes [Dud16, Her20]. The emergence of underlying approximate symmetries and their breaking in phenomena such as deformation, clustering, and pairing, are now being investigated using *ab initio* calculations, EFT methods, and symmetry-adapted many-body techniques.

This progress provides the opportunity to ground a quantitative understanding of old phenomenological models in the fundamentals of nuclear physics. This will bring new insights into the complex dynamics of exotic nuclei, and will expose the domain of validity and improve the precision of phenomenological models, making them more accurate predictive tools for the study of nuclei.

Achieving this will be hardest in particularly interesting cases. Two examples are very exotic systems with large proton-neutron imbalance that are close or at the decay thresholds and systems where there is a complex interplay of clustering and decay. To make progress on these problems forefront computing and novel ideas will be needed.

CROSSING FROM BOUND STATES TO THE CONTINUUM: Which combinations of protons and neutrons can be bound by the strong force to produce a nucleus? This intriguing and yet basic question is at the heart of low-energy nuclear physics. It motivates the exploration of the driplines (where additional protons and neutrons drip out of the nucleus) and provides a stringent test of our understanding of atomic nuclei. One of the main themes of contemporary nuclear theory is the unification of nuclear structure and reactions. We take up the topic of nuclear reactions in the next subsection but point out already here that such a unification requires the proper inclusion of decay channels and couplings to the continuum of scattering states [Joh20].

Open quantum systems (cf. Sec. 1.4) provide a paradigm in which the boundary between structure theory and reaction theory is inevitably blurred: weakly-bound states of the quantum many-body system and its properties at high excitation energies are inextricably interwoven. This near-threshold regime tests nuclear forces in isotopes with extreme neutron-to-proton ratios and close to particle emission thresholds, displays new exotic forms of radioactivity, and demonstrates the interplay between continuum couplings and emergent phenomena [Baz22]. A unified description of structure and continuum dynamics has emerged in light nuclei over the past seven years. In the next decade, the exploration of these essential topics will extend into the medium-mass region of the nuclear chart. This will require developments to tackle continuum couplings beyond few-body dynamics, to extend the predictive power of nuclear forces and theoretical approaches near the driplines, and to build a tower of EFTs to rigorously link together all near-threshold and emergent phenomena with each other and their underlying degrees of freedom. Near-threshold physics also opens a multidisciplinary window into universality, a phenomenon present

in all quantum systems dominated by large scattering lengths, and expected to play a prominent role in the understanding of effective few-body dynamics in exotic nuclei [Kie21, Tew22].

1.1.2 NUCLEAR REACTIONS

Nuclear reaction theory describes collisions between two or more nuclear species and plays an important twofold role in the context of low-energy nuclear physics. First, it connects experimental observables obtained at accelerated-beam facilities with specific aspects of nuclear structure. Second, it addresses processes that are essential for a variety of applications in nuclear astrophysics, nuclear energy, medicine, security, and industry. In its first role, it is essential to unlock the full discovery potential of FRIB, ATLAS, and the ARUNA labs; in the latter, it is at the basis of a successful implementation of the corresponding applications.

Ab initio descriptions of reactions have made tremendous progress in the last decade. Reactions in light nuclei – such as the cross section for the deuterium-tritium fusion reaction that is the basis for efforts to harness fusion energy at NIF and other facilities around the world – can now be computed without any uncontrolled approximations. There are many opportunities to extend this approach to heavier targets and projectiles. Complementary approaches which reduce the nuclear many-body problem to a description in terms of a few active degrees of freedom are needed to address the many reactions involving medium-mass and heavy nuclei. The development of nucleon-nucleus effective interactions, rooted in *ab initio* nuclear structure and based on controlled approximations, offers many opportunities [Joh20, Heb22]. It will also be critical to further develop systematic approaches to clustered cases where either the target nucleus or the projectile has a substructure that can be activated as part of the reaction dynamics and where an effective three- (or higher-) body treatment is needed.

As one moves away from beta stability and crosses exotic shell closures, the level densities relevant for important astrophysical processes, such as particle capture, tend to decrease rapidly. Then, direct reaction mechanisms, where the projectile interacts with specific states in the target nucleus, will compete with compound reaction mechanisms that involve the formation of a thermally equilibrated intermediate nucleus. The rigorous description of this transition between very different reaction mechanisms is a challenging and timely opportunity, since during the next decade many reactions in which this transition occurs will be measured at rare-isotope beam facilities around the world.

In the quest for a quantitatively accurate and predictive theory of nuclear reactions, uncertainty quantification will continue to play a central role. The relatively recent incorporation of sophisticated statistical methods to the reaction theory toolbox has already yielded promising results. Coupling uncertainties originating from nuclear structure models with the ones specific to the reaction formalism employed is a new frontier that will become increasingly relevant in the FRIB era.

Precision characterizations of the quark-gluon plasma created in high-energy nuclear collision experiments require detailed knowledge of the low-energy structure of the colliding nuclei. Theoretical models of the quark-gluon plasma would benefit from the results of nuclear structure calculations, and both can be confronted with data from planned light-ion collisions at high-energy colliders.

1.1.3 NUCLEAR EQUATION OF STATE AND HEAVY ION COLLISIONS

The nuclear equation of state (EOS) links the density, pressure, energy, temperature, and composition of strongly interacting dense matter. At densities up to a few times the nuclear saturation density, the degrees of freedom that enter the calculation of the EOS are nucleons while at higher densities other degrees of freedom, such as hyperons, or even quarks, might appear. For densities up to about twice nuclear saturation density, the nuclear EOS can be

calculated with theoretical uncertainties. Nuclear matter that is nearly symmetric in the number of neutrons and protons can be probed in heavy-ion collisions, while our understanding of neutron-rich matter can be tested in observations of neutron stars, the most compact directly observable remnants of stellar collapse. Such tests of neutron-rich matter also help us better understand the physics of neutron-rich nuclei investigated at rare isotope beam facilities. These disparate environments and observables are connected through the nuclear EOS.

We stand on the cusp of an era that will offer an unprecedented wealth of data on the EOS but will also demand predictive and precise theory. Gravitational-wave detectors will likely soon be observing several neutron-star mergers per year [Col22]. The resulting data, when interpreted using forefront astrophysics and nuclear theory, will address fundamental questions, such as: What is the nature of strongly interacting matter at high densities? How are heavy elements created in the universe? What are the fundamental interactions among nucleons in cold dense matter? Are exotic forms of matter, like quark matter, realized in neutron-star cores?

Neutron-star merger observations will constrain the tidal deformability for various neutron-star masses, thereby tightening bounds on the nuclear EOS. Such observations together with their electromagnetic counterparts will provide us with multiple observables that test theories of dense matter in the universe's most extreme environments and also illuminate the r-process mysteries. Data from observations of isolated neutron stars, e.g., X-ray pulse profiles or cooling curves, can provide complementary EOS constraints. High-fidelity nuclear-physics inputs with quantified uncertainties – for example, theoretical calculations of the EOS and consistent neutrino cross sections in dense matter – are needed to extract as much information as possible from future observations. This requires a broad improvement of dense matter theory over a wide range of densities, temperatures, and isospin asymmetries, covering conditions from crust to core to those encountered in explosive astrophysical environments. Reliable nuclear-physics input provides valuable prior information for data analyses of neutron-star observations, allows theorists to better constrain the actual conditions of a neutron star merger, and to make robust connections to laboratory experiments on Earth. Pushing this input to higher densities is key to reveal the secrets of neutron-star mergers. This information is also crucial to determine the density at which chiral EFT no longer accurately describes dense matter. The combination of chiral EFT with modern computational tools, e.g., machine learning, emulators, and Bayesian inference, could help us do that.

Multi-messenger signals from neutron stars and their collisions, especially involving heavy neutron stars or post-merger remnants, are sensitive to the EOS at densities that are too large to use Chiral EFT. In this regime, multi-messenger analyses of astrophysical data typically use physics-agnostic parameterizations of the EOS which permit the widest range of physical behavior in neutron-star cores. While such studies produce model-independent constraints on the EOS, they do not tell us how QCD produces that EOS. To understand that, we need to ensure that microscopic models of neutron-rich dense matter at a few times nuclear saturation density are anchored in QCD and come with quantified uncertainties. Comparisons with physics-agnostic approaches can then illuminate the composition of matter in this regime. Such microscopic models will also be important to connect theoretical calculations of neutron-star matter, as well as astrophysical observations, to heavy-ion collision experiments at accelerator facilities around the world.

Heavy-ion collision experiments provide us with a bridge between the regimes of low and high densities and thereby provide a complementary window on the EOS [Dan02, Hut22]. FRIB and FRIB400 [FRIB400] will offer a golden opportunity to probe the EOS of dense nuclear matter up to about twice the saturation density. However, to capitalize on these investments, uncertainties in the EOS constraints from experiments need to be reduced. Robust inferences from the experimental data will require more accurate transport theory and continued development of

associated hadronic transport codes. There are concerns about the loss of critical expertise in the field of hadronic transport within the US.

The next decade will be a “Golden Age” of neutron-star observations. The opportunity is there to pin down the nuclear EOS, infer the existence of exotic forms of matter, and constrain the strong interactions that govern the most extreme environments in the universe. To fully realize the discovery potential inherent in rare-isotope beam and multi-messenger data we need to foster interdisciplinary, multiphysics collaborations among observers, experimentalists, and theorists with a broad range of expertise and backgrounds.

1.1.4 HEAVY NUCLEI AND FISSION

Some of the most fundamental and intriguing questions in nuclear science involve heavy nuclei. Especially puzzling is the far end of the table of isotopes, which remains largely uncharted. How heavy can a nucleus be? Are there new magic numbers beyond ^{208}Pb ? How can we make such nuclei? The answers to such questions go far beyond nuclear science since they are indispensable to understanding where exactly Mendeleev’s Periodic Table of Elements ends.

Superheavy elements also play an important role as the end point of nucleosynthesis. Theoretical research into their properties is thus essential since the heaviest neutron-rich nuclei involved in the *r*-process will remain out of reach of experimental facilities for decades. What is the structure of such nuclei? What are their lifetimes? How do they decay? More generally, simulating the complex set of nuclear reactions that take place in astrophysical environments requires knowing all possible formation mechanisms and decay modes of every single nucleus in the nuclear chart [Mum16]. Quantifying how the uncertainties of such data impact astrophysical simulations is thus key to elucidating where exactly heavy elements are made in the Cosmos. Such a task cannot be reliably achieved without a consistent model of nuclear structure, reactions and decays that can be applied across the entire mass table. Access to fully correlated, symmetry-preserving, many-body wavefunctions in heavy nuclei is also important for computations of the nuclear matrix elements needed for exploration of signals of physics beyond the Standard Model, e.g., neutrinoless double-beta decay in heavy nuclei and the neutron electric dipole moment of nuclei in heavy neutral atoms.

Nuclear density functional theories address these questions in a single, consistent framework [Sch19]. A single energy density functional can be used to predict nuclear observables ranging from binding energies and radii to β -decay rates to spontaneous fission half-lives. This consistency provides a rigorous framework for the determination of nuclear uncertainties and the use of the resulting nuclear data in applications. The development of quality energy functionals is indispensable to tackle the challenges mentioned above.

There are three prominent opportunities that can drive this development forward over the next decade. First, anchoring the form of the functional to our modern theory of nuclear forces based on Chiral EFT would allow us to pursue systematic improvements and to better quantify uncertainties. Second, irrespective of their mathematical expression, energy functionals need to be calibrated to experimental data. This is fertile ground for state-of-the-art ML/AI techniques, such as the design of high-precision emulators and the application of Bayesian statistics for inference or experimental design [Boe22]. While many of these methods have become standard, they will need to be considerably extended to enable end-to-end propagation of uncertainties from the underlying functional to the model predictions of complex observables such as, e.g., decay rates, the properties of the neutron star crust or *r*-process abundances. Third, as experimental facilities worldwide push towards the neutron dripline for heavier systems, there will be increasing demands for high-precision predictions of quantities such as the low-lying energy spectrum of very neutron-rich, heavy nuclei and their decay schemes. Such observables are very sensitive probes of the structure of nuclei. This presents us with opportunities to further develop tools such as multi-reference energy-density functionals and beyond-mean-field methods. The results of such calculations then provide the foundations

for microscopic, predictive models of nuclear reactions. While the theoretical framework has been long known, we have reached the point where computational capabilities are sufficient to solve real-life problems.

All these developments are needed for the first-principles description of nuclear fission, one of the most formidable problems in nuclear science [Sch22]. Fission causes the decay of superheavy elements and is the primary mechanism that ends *r*-process reactions. It is also a key method to produce neutron-rich isotopes at facilities such as ATLAS. A predictive model of this complex phenomenon is useful not just from a pure-science perspective, but also because it can address problems related to nuclear waste or help in the design of new generations of nuclear reactors. The renaissance in fission science that has occurred over the last decade has been largely driven by progress in leveraging massively parallel computing platforms [Ben20]. Experiments at FRIB, especially those that employ the future High Rigidity Spectrometer [HRS], will provide a wealth of data to better constrain theoretical models of fission and make them predictive enough for applications in the very neutron-rich nuclei involved in astrophysical processes. The significant progress of the last few years in developing quantum-mechanical models of large-amplitude nuclear dynamics that incorporate important physics effects such as dissipation, fluctuations or non-locality has opened new avenues of research: integrating these developments into a unified, consistent theory capable of accurately predicting a wide range of fission observables is going to be a challenge for the next decade; it will allow fission theory to capitalize on accompanying computational and experimental investments. In the near term, these advances can be made within extensions of time-dependent density functional theory. That framework can be applied not only to fission or heavy-ion collisions, but also to describe the emergence of pasta phases in the neutron star crust.

1.1.5 CONNECTIONS TO OTHER FIELDS

STRONGLY CORRELATED FERMIONIC SYSTEMS: Quantitative and qualitative understanding of strongly-correlated fermionic systems is at the heart of nuclear physics, but this problem is also ubiquitous in quantum chemistry, ultracold atomic gases, and condensed matter. Nuclear theory has been at the forefront of progress in this multidisciplinary area and continues to benefit from developments in other fields of physics. The unitary Fermi gas provides insights into the physics of nuclei and neutron stars, and halo nuclei and low-energy reactions with neutrons near the dripline provide a concrete realization of conformal symmetries.

QUANTUM INFORMATION SCIENCE IN NUCLEAR THEORY: Nuclear theory is also benefiting from advances in quantum information science. The development of quantum algorithms to solve the many-body problem could lead to a dramatic acceleration of the field, and studies of entanglement measures in nuclei could provide new insights and novel ways to address the problem. The next decade will also see the beginning of attempts to simulate real-time quantum dynamics of strongly interacting matter on quantum hardware.

OPEN QUANTUM SYSTEMS: Weakly bound and unbound nuclei are open quantum systems, i.e., systems coupled to an environment of scattering states that cannot be treated as isolated. They present generic features also found in atoms, molecules, quantum dots, quantum optics devices, etc. Open quantum systems provide valuable insight into fundamental problems of quantum mechanics related to irreversibility and decay, measurement the collapse of the wave function, and the role of entanglement in the dynamics of quantum systems.

EMERGING STATISTICAL METHODS: Quantifying model uncertainty is essential to continued progress on the suite of problems described here. EFT offers a natural way to do this, but there are several crucial nuclear-physics problems for which no EFT presently exists. Quantification of model uncertainty is still possible in these contexts. Models that emphasize complementary aspects of the physics can be combined using novel statistical methods such

as Bayesian Model Mixing, thereby leveraging their various insights, and yielding an overall error bar that includes model uncertainty.

NEEDS

The base program is at the heart of everything theorists do. Many of the most important and original ideas in nuclear theory are born in research groups with a single principal investigator (PI). Healthy funding for these researchers, as well as the postdoctoral researchers and graduate students working with them, will produce a continued flow of innovative theory research. Base theory research also plays a key role in enabling the full realization of the investment in forefront experimental facilities since it is through the work of many small groups that mathematical models for the description of nuclear properties are advanced and most experiments are motivated and interpreted. The situation is similar regarding the flow of ideas for new calculations and numerical methods at advanced computing facilities. Longer grant cycles allow for better strategic choices regarding research direction, permit PIs and their students to pursue potentially disruptive research directions, and facilitate serendipitous discoveries.

Collaborative nuclear theory grants, such as NSF Theory Hubs and DOE Topical Collaborations, accelerate progress on key nuclear-physics problems. They bring theorists with different expertise and skills together and encourage them to focus on a particular problem for a well-defined period. But they work best when there is a well-defined pathway to the solution of that problem, and so, of necessity, must build on existing theory insights from the base program.

Grants that explore and exploit synergies with other fields are very beneficial to theoretical nuclear physics. SciDAC at the DOE and the Office of Advanced Cyberinfrastructure grants at the NSF have encouraged our community to reach beyond our usual networks and find collaborators in other fields. Can this model be extended to collaboration with cross-cutting areas, other subfields of physics, and working with experimental colleagues?

The FRIB Theory Alliance is a success story. It will embrace opportunities to evolve over the next decade in response to the changing needs of the FRIB community. The FRIB-TA has now funded five bridge positions, and two of those faculty have won Early Career awards. The young scientists selected to participate in the FRIB Theory Fellow program have produced excellent research and have gone on to permanent positions at prominent institutions in our field. Meanwhile other activities of the FRIB-TA such as Topical Programs, Summer Schools, and Dialogs, promote intellectual engagement of researchers at all career stages with key problems in our field.

The Institute for Nuclear Theory (INT) has greatly benefited the theory community and nuclear physics. A strong INT leads to better science across our whole field because it fosters new ideas, collaborations, and talent.

BIBLIOGRAPHY

[Baz22] D. Bazin *et al.*, *Perspectives on few-body cluster structures in exotic nuclei*, [arXiv:2211.06281](https://arxiv.org/abs/2211.06281).

[Ben20] Michael Bender *et al.*, *Future of Nuclear Fission Theory*, *J. Phys. G.: Nucl. Part. Phys.* 47, 113002 (2020).

[Boe22] A. Boehnlein *et al.*, *Colloquium: Machine learning in nuclear physics*, *Rev. Mod. Phys.* 94, 031003 (2022).

[Cir22] V. Cirigliano *et al.*, *Towards Precise and Accurate Calculations of Neutrinoless Double-Beta Decay*, *J. Phys. G* 49, 120502 (2022).

[Col22] A. Colombo *et al.*, *Multi-messenger Observations of Binary Neutron Star Mergers in the O4 Run*, *Astrophys. J.* 937, 79 (2022).

- [Dan02] P. Danielewicz, R. Lacey, and W. G. Lynch, *Determination of the equation of state of dense matter*, Science 298, 1592-1596 (2002).
- [Dud16] See articles in J. Dudek (editor), [Focus issue to celebrate the 40 year anniversary of the 1975 Nobel Prize to Aage Niels Bohr, Ben Roy Mottelson and Leo James Rainwater](#).
- [Epe09] E. Epelbaum, H. -W. Hammer, and Ulf-G. Meißner, *Modern theory of nuclear forces*, Rev. Mod. Phys. 81, 1773 (2009).
- [Erl12] J. Erler *et al.*, *The limits of the nuclear landscape*, Nature 486, 509 (2012).
- [Fur21] R. J. Furnstahl, H.-W. Hammer, A. Schwenk, *Nuclear Structure at the Crossroads*, Few-Body Syst. 62, 72 (2021).
- [FRIB400] [FRIB400: The Scientific Case for the 400 MeV/u Energy Upgrade of FRIB](#), FRIB White Paper.
- [Ham20] H.-W. Hammer, Sebastian König, and U. van Kolck, *Nuclear effective field theory: Status and perspectives*, Rev. Mod. Phys. 92, 025004 (2020).
- [Her20] H. Hergert, *A guided tour of ab initio nuclear many-body theory*, Front. Phys. 8, 379 (2020).
- [Heb22] C. Hebborn *et al.*, *Optical potentials for the rare-isotope beam era*, [arXiv:2210.07293](#).
- [HRS] [A High Rigidity Spectrometer for FRIB](#) Whitepaper authored by the nuclear science community (2017).
- [Hut22] S. Huth *et al.*, *Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions*, Nature 606, 276 (2022).
- [Joh20] C. W. Johnson *et al.*, *White paper: From bound states to the continuum*, J. Phys. G 47, 123001 (2020).
- [Kie21] A. Kievsky, M. Gattobigio, L. Girlanda, and M. Viviani, *Efimov physics and connections to nuclear physics*, Ann. Rev. Nucl. Part. Sci. 71, 465 (2021).
- [Kol22] K. Kolos *et al.*, *Current nuclear data needs for applications*, Phys. Rev. Research 4, 021001 (2022).
- [Mac11] R. Machleidt, and D. R. Entem, *Chiral effective field theory and nuclear forces*, Phys. Rep. 503, 1 (2011).
- [Mum16] M.R. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, *The impact of individual nuclear properties on r-process nucleosynthesis*, Prog. Part. Nucl. Phys. 86, 86 (2016).
- [Ots20] T. Otsuka, A. Gade, O. Sorlin, T. Suzuki, and Y. Utsuno, *Evolution of shell structure in exotic nuclei*, Rev. Mod. Phys. 92, 015002 (2020).
- [Roc20] N. Rocco, *Ab initio Calculations of Lepton-Nucleus Scattering*, Front. Phys. 8, 116 (2020).
- [Sch19] [Energy Density Functional Methods for Atomic Nuclei](#), Ed. N. Schunck, IOP Publishing (2019).
- [Sch22] Nicolas Schunck and David Regnier, *Theory of Nuclear Fission*, Prog. Part. Nucl. Phys. 125, 103963 (2022).
- [Tew20], I. Tews, Z. Davoudi, A. Ekström, J.D. Holt, J.E. Lynn, *New Ideas in Constraining Nuclear Forces*, J. Phys. G: Nucl. Part. Phys. 47, 103001 (2020).
- [Tew22] I. Tews *et al.*, *Nuclear Forces for Precision nuclear physics: A collection of perspectives*, Few-Body Syst. 63, 67 (2022).

2 NUCLEAR STRUCTURE AND REACTIONS EXPERIMENTS

INTRODUCTION

We are approaching the 130th anniversary of the discovery of radioactivity by Becquerel in 1896. While we have made immense progress in our understanding of the atomic nucleus and its interactions, in many ways, we continue to explore the same overarching questions which arose at the birth of nuclear physics more than a century ago. Today, however, we are at the brink of a new era of discovery.

The subfield of nuclear structure and reactions aims to measure, explain, and use nuclei, which entails a concerted effort toward an understanding of the underlying nature of the nucleus and the limits to their existence. The challenges posed already by the National Research Council report of 2013 remain relevant today, with the question *“How does subatomic matter organize itself and what phenomena emerge?”* driving both experimental and theoretical inquiries.

Time has not stood still over the decade since the NRC report, nor the years since the last Long Range Plan in 2015. The field of nuclear structure and reactions has made impressive strides; from the application of a broad range of theoretical approaches across the entirety of the nuclear chart to advances in experimental systems enabling increases in sensitivity and measurement reach. Looking forward, this subfield is on the brink of a new era with the Facility for Rare Isotope Beams (FRIB) now online and ramping to its final beam power, and a community of scientists ready to make optimal use of not only FRIB, but also the ATLAS and ARUNA [ARUNA] facilities, available computing resources, and technological developments.

The following sections address the questions posed to the Nuclear Structure and Reactions working groups in the framework of the 2022 Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics held at Argonne National Laboratory. The contents of these sections derive largely from the community input presented during the working group sessions on the topics of nuclear structure and reactions experiments. All presented material is archived online at the [Town Hall Meeting webpage](#).

ACCOMPLISHMENTS SINCE THE LAST LONG RANGE PLAN

In a field with the breadth of Nuclear Structure and Reactions, even limiting consideration to primarily experimental work, providing a complete summary of accomplishments since the last Long Range Plan is a virtually impossible task. The achievements outlined under the subsections below are necessarily incomplete but serve to highlight a representative snapshot of the activities ongoing in this vibrant and broad community.

2.1.1 THE LIMITS OF NUCLEAR EXISTENCE

The limits of the nuclear landscape, in all directions – the proton dripline, the neutron dripline, the lightest interacting systems and the heaviest isotopes – provide challenges to our field, both in terms of the experimental efforts to study these most exotic systems, and on the theory side in understanding the phenomena that are uncovered. At the very limits of experimental reach is often where new phenomena and aspects of the nucleus are revealed, and where theoretical frameworks are confronted and tested at the limits of their predictive power.

TO AND BEYOND THE PROTON DRIPLINE - In recent years, experiments have pushed toward – and even past – the proton dripline across a broad range of masses, leading to the discovery of new isotopes and new decay modes. These systems offer a unique opportunity to study continuum coupling effects and characterize the transition from a closed to an open quantum system.

- The heaviest-known proton emitter ^{185}Bi has been reinvestigated in an experiment with the FMA at ATLAS. In addition to the ground-state, a longer-lived isomeric proton-emitting state was found. These data showed the ordering of low- and high-spin states is reversed in this nucleus compared to heavier odd- A Bi isotopes.
- The super-allowed α -decay of the self-conjugate nucleus ^{108}Xe to the double-magic nucleus ^{100}Sn was observed for the first time in experiments with the FMA at ATLAS.
- Along $N=Z$, an example of isobaric-spin-symmetry breaking has been identified in the $^{73}\text{Sr}/^{73}\text{Br}$ mirror pair, where these nuclei have different ground-state spins.
- Invariant-mass spectroscopy studies at NSCL have led to the discovery of the two-proton and multi-proton ground-state emitters ^9N , ^{11}O , ^{13}F , ^{17}Na , and ^{18}Mg . The most exotic cases, ^{18}Mg and ^9N , decay by the emission of four and five protons respectively. In all cases, protons are emitted in sequential steps of single and prompt-two-proton decay.

β -delayed proton emission of the neutron-rich ^{11}Be isotope was observed with the prototype AT-TPC at TRIUMF. It was suggested that this decay proceeds through an unknown near-threshold state in ^{11}B whose structure was modified by its proximity to the proton continuum. Subsequent measurements at the ReA3 facility at NSCL and the John D. Fox Superconducting Linear Accelerator Laboratory at Florida State University independently confirmed the presence and properties of this resonance.

MAPPING AND UNDERSTANDING THE NEUTRON DRIPLINE - On the neutron-rich side of the nuclear chart, the dripline extends farther from the stable nuclides, and the exact position of the dripline limit remains an open question above $Z=10$. Beyond the basic question of the location of the dripline, this region is truly terra incognita, with potentially substantial structural changes possible in very weakly bound nuclei as coupling to the neutron continuum becomes important. Such weakly-confined and open quantum states present a unique opportunity to investigate the nuclear force through the intertwined relation of nuclear structure and reaction phenomena. Halo nuclei are one example of the type of structures which may emerge as the familiar nuclear models assuming a harmonic-oscillator potential become invalid.

- Quasi-elastic knockout of an α particle induced by a proton target on ^8He was performed and used to identify a $4n$ (tetra-neutron) structure with a decay energy of 2 MeV. Debate continues as to whether this is a genuine resonance or a final-state effect.
- The isotope ^{39}Na was observed at RIBF, confirming the location of the neutron dripline to $Z=10$, and likely to $Z=11$. This measurement pushes the mapping of the dripline as far as it can go without the beam intensity of FRIB.
- Invariant-mass studies with MoNA at the NSCL have shown the ability to determine the type of multi-neutron emission and confronted the challenge of interpreting systems such as ^{31}Ne with high-densities of neutron resonances, which is not a unique challenge when approaching Islands of Inversion along the dripline.

First spectroscopy of ^{40}Mg has shown a substantial change in the excitation spectrum of this heaviest Mg isotope relative to its lighter $^{36,38}\text{Mg}$ neighbors, possibly indicating the impact of the continuum on the structure in this near drip-line nucleus.

THE LIMITS OF MASS AND CHARGE - The heavy and superheavy nuclei [SHE] represent the limits of nuclear mass and charge, with the very existence of the superheavy systems relying on the delicate interplay between the Coulomb repulsion between protons and the stabilization from the attractive nuclear force and its associated shell

effects. Progress since 2015 in this area has been substantial, with the addition of four new elements to the periodic table – Nihonium ($Z=113$), Moscovium ($Z=115$), Tennessine ($Z=117$) and Oganesson ($Z=118$) – and measurements informing our understanding of their structure.

- The first definitive determination of the mass number A of a superheavy element was made for ^{288}Mc at the BGS and FIONA (LBNL), providing an anchor for the position of the superheavy isotopes relative to the rest of the nuclear chart.
- In-beam and decay spectroscopy using the powerful setup of the Argonne Gas-Filled Analyzer (AGFA) plus Gammasphere and the X-array have enabled detailed measurements in Rf, Md, Lr and No isotopes. Identification of the band structures and association of these structures with specific Nilsson orbitals informs on the shells which are most relevant at the Fermi surface of the SHE.

2.1.2 EVOLUTION OF NUCLEAR STRUCTURE - SHELLS, SHAPES AND COLLECTIVITY

It has been nearly 60 years since the Nobel Prize was awarded to Goeppert Mayer and Jensen for the framework of the Shell Model to describe the structure of nuclei. While this model and the relatively simple potential it describes has succeeded near β -stability, it is now well known that moving away from the stable isotopes results in an often-dramatic rearrangement of the proton and neutron single-particle states. With this rearrangement, a result of the residual nucleon-nucleon interaction, there are also emergent nuclear characteristics, including development of quadrupole and higher-order deformations, co-existence of multiple deformed configurations nearby in energy, and other collective behavior. Detailed experimental information away from the valley of stability is key to building a comprehensive understanding of the interactions governing the nuclear system.

CHANGING MAGIC NUMBERS - The “Islands of Inversion”, near $N=20$, $Z=12$ and $N=40$, $Z=24$ are clear examples of evolving shell structure away from stability, where the energetics of single-nucleon states are such that np - nh excitations across expected shell or subshell gaps dominate nuclear configurations. However, examples are not limited to these regions – additional evidence for modified shell structure continues to appear across the nuclear chart.

- While there is evidence for viewing ^{24}O as a doubly-magic nucleus, two experiments probing the structure of the ^{25}F ground state provide evidence that this nucleus cannot be viewed simply as $^{24}\text{O}+p$, or in other words the $N=16$ subshell closure may not hold even in the F isotopes.
- The Ca isotopes with a closed $Z=20$ proton shell have continued to be a focus of study. Radii measurements extending to $N=32$ in both Ca and the neighboring K raise questions about the strength of the subshell closure expected at this neutron number, while first spectroscopy measurements pushing to $N=36$ suggests a structural change toward more collective structure. The question of the $N=40$ subshell closure in Ca remains a pressing one, certain to be explored in the next several years.

THE INTERSECTION OF STRUCTURE AND REACTIONS - Nuclear structure and reactions have always been, and will continue to be closely linked. Reactions may be chosen for a measurement based on their selectivity to probe specific final states, or indeed their dynamics is the topic of interest. Cross sections for nucleon addition or removal are connected, via the spectroscopic factor, to the occupation of particular single-particle states, after a theoretical interpretation. However, this connection is often more complex than ideal, and there remain many open questions.

- The growing body of knowledge for inclusive cross sections of intermediate-energy nucleon knockout reactions shows a clear trend for the suppression factor (ratio of experimental to calculated cross sections) as a function of ΔS , the difference in binding energy between the removed and spectator nucleon species.

- Absolute cross sections for the addition of *s*- and *d*-wave neutrons to ^{14}C and ^{14}N have been determined simultaneously via the (*d,p*) reaction at 10 MeV/u, providing data points for transfer with ΔS around -20 MeV for the $^{14}\text{C}+n$ system and $+8$ MeV for $^{14}\text{N}+n$. The population of the $1s_{1/2}$ and $0d_{5/2}$ orbitals for both systems is reduced by a factor of approximately 0.5 compared with the independent single-particle model, or about 0.6 when compared with the shell model. This finding strongly contrasts with results deduced from intermediate-energy knockout reactions between similar nuclei on targets of ^9Be and ^{12}C .
- Results from higher-energy processes at GSI, namely (*p,2p*) nucleon removal on O and C isotopes shows no dependence on the difference in separation energy (ΔS), in agreement with transfer and (*e,e'p*) measurements and in contrast to nucleon knockout on Be and C targets.

PEAR-SHAPED NUCLEI - While quadrupole deformation is ubiquitous across the nuclear chart, stable higher-order deformation has remained somewhat elusive. However, in the last decade, a number of examples of octupole deformation have emerged and significant effort has gone into characterizing the degree and stability of this deformation. These studies have laid the groundwork for future work toward characterizing candidates for EDM searches.

- A first Coulomb-excitation (Coulx) experiment was performed to determine the shape of the ground state of ^{223}Ra , using the powerful combination of GRETINA and CHICO-2 at ANL.
- The octupole collectivity of $^{144,146}\text{Ba}$ was characterized using CARIBU beams at ANL, determining enhanced octupole collectivity and a static octupole shape based on the measured $B(E3)$ transition probabilities, while results on the collectivity of ^{143}Ba rather favor an octupole vibrational picture.

BREAKING AXIAL SYMMETRY: TRIAXIAL NUCLEI - We know today that most nuclei are axially symmetric, either spherical or ellipsoidal (prolate or oblate) – however, it was around 1960 that nuclei that are triaxial in their ground states were first predicted, and it was initially assumed that rigidly triaxial nuclei were common. However, the majority of nuclei which are not axially symmetric have been found to be “soft”, far from rigidly deformed. Thus, the quest for ground-state triaxiality continues.

- Experiments were performed at ANL, NSCL at Michigan State University, and the Accelerator Laboratory at the University of Kentucky to determine the degree of triaxiality of ^{76}Ge and ^{76}Se . These studies inform searches for the $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$ neutrino-less double beta decay and are important steps towards constraining the corresponding nuclear matrix element as model predictions vary significantly.
- Coulx of ^{110}Ru at the CARIBU facility at ANL with GRETINA showed strong evidence for a triaxial shape for levels near the ground state, in contrast to the more common assertions of triaxiality at high angular momenta.

2.1.3 PRECISION MEASUREMENTS IN THE NUCLEAR SYSTEM

“Precision” measurements can be interpreted in multiple ways, but we refer here to the range of experiments probing (primarily ground-state) properties including nuclear masses, radii and electromagnetic moments. These are experiments which aim to measure observables to 1 part in 10^6 or better for masses, or laser frequency in isotope-shift measurements. With the precision of such experiments, these types of studies offer a powerful test of nuclear models, and indeed of fundamental interactions.

- A precision mass measurement of the $N=Z=40$ self-conjugate nucleus ^{80}Zr at LEBIT shows that this nucleus is lighter, or much more strongly bound than predicted. This is attributed to the deformed shell closure at $N=Z=40$ and the large Wigner energy.
- Measurements using CARIBU beams at the CPT have provided precision masses for nuclei in the light rare-earth region, including identification and measurement of long-lived isomers in odd-odd deformed nuclei, by taking advantage of the strength of the phase imaging ion cyclotron resonance technique.
- As previously mentioned, charge radii measurements in the Ca isotopic chain have added to the body of knowledge at $Z=20$. Systematic measurements, moving to the neutron-deficient isotopes as well as toward the most neutron rich, demonstrate the importance of experiments along isotopic chains to impact developments of global models of nuclei.

2.1.4 NUCLEAR STRUCTURE TO ASTROPHYSICS

While nuclear structure and reactions are separated here from nuclear astrophysics, the connections between these research areas are undeniable. From masses to decay half-lives, there are numerous obvious nuclear-structure properties which feed directly into nuclear astrophysics models. There are also somewhat less prominent aspects of structure and reactions which have an equally strong impact, and which have been explored substantially in recent years.

NUCLEAR EQUATION OF STATE - The nuclear equation of state (EOS) has far-reaching implications, not only for the understanding of the atomic nucleus itself, but also in the context of astrophysical processes and environments, such as neutron stars which are the definition of asymmetric nuclear matter. The symmetry energy contribution to the EOS specifically is constrained predominantly by terrestrial experimental work in nucleus-nucleus collisions. While in the future gravitational wave observations will undoubtedly continue to add complementary constraints, much progress has been made since 2015 based on laboratory experiments.

- Experiments at Texas A&M showed that the equilibration of protons and neutrons in nuclear matter follows first-order kinetics with a mean lifetime of equilibration of 0.3 zs.
- The neutron skins of ^{48}Ca and ^{208}Pb have been extracted from parity-violation in elastic scattering of polarized electrons at the Thomas Jefferson National Accelerator Facility.
- The slope of the symmetry energy at saturation density has been inferred from the differences in the charge of the mirror pairs ^{36}Ca - ^{36}S and ^{54}Ni - ^{54}Fe . This was facilitated from the first measurements of the charge radii of ^{36}Ca and ^{54}Ni at NSCL using collinear laser spectroscopy.
- At supra-saturation densities, the slope of the symmetry energy has been constrained from the spectral pion ratio measured with the $\text{S}\pi\text{RIT}$ TPC.
- With the combined analysis of neutron-star mergers, electron scattering, reactions between nuclei, and nuclear properties, the symmetry energy has some experimental constraints from $0.2\rho_0$ to $2\rho_0$ (ρ_0 = saturation density), however, with large uncertainties and sparse data as $2\rho_0$ is approached.

RADIATIVE CAPTURE ACROSS THE NUCLEAR CHART - Where direct measurements of reaction rates are not possible or experimentally challenging (such as neutron-capture rates), indirect approaches become critical. Such approaches can require knowledge of statistical nuclear properties, including γ -ray strength functions. While these have been measured near stability, the recent years have seen a significant extension of the available data to systems away from stability.

- The β -Oslo method has been used to constrain the γ -ray strength functions in exotic nuclei including ^{69}Ni , which is used to make a prediction for the $^{69}\text{Ni}(n, \gamma)^{70}\text{Ni}$ reaction rate. The refinement in the reaction rate

prediction based on the measured γ -ray strength function resulted in dramatic reduction in the error of r -process abundance predictions associated with this reaction rate.

- Significant progress has been made in surrogate reaction techniques for radiative capture. Experimental data from (d, p) transfer reactions, when combined with recent advances in reaction theory, now enables the determination of neutron capture rates for short-lived nuclei.

ASTROMERS - Low-lying, high-spin isomeric states have traditionally been neglected in astrophysical models, apart from the high-profile $^{26}\text{Al } 0^+$ isomer. However, it is anticipated that many isomers exist with the potential to alter the nucleosynthetic path. Knowledge of the structure of these isomers is critical to understanding explosive nucleosynthesis, while predictions of isomer production in various reaction mechanisms is similarly important.

- Nine nuclei with isomers in the vicinity of ^{130}Sn have been identified as having the potential to significantly impact the rapid neutron-capture process; additional structural information is needed to firmly assess their impact.
- Transfer reactions on the ground-state and isomeric state in ^{130}Sn have been performed, with direct implications for the p -wave states important for the r -process.

OPPORTUNITIES FOR THE NEXT DECADE

As previously mentioned, the nuclear structure and reactions community is on the doorstep of a new era, with FRIB beginning operations. However, it is not only FRIB that is extending what is experimentally possible in the next decade. Continuing developments of experimental end-stations enhance the sensitivity of each measurement, while upgrades and expanded capabilities at ATLAS, ARUNA and key national laboratory facilities expand the horizons of what is possible. In the following sections, a taste of what will be possible by 2030 is presented – as with accomplishments, this is not a complete roadmap, but rather a sampling of results which may well be among the scientific headlines in the coming years.

2.1.5 THE LIMITS OF NUCLEAR EXISTENCE

With the availability of FRIB beams and increasingly sensitive detector systems, we are uniquely positioned to push our knowledge of the proton and neutron driplines up the nuclear chart, and to extend beyond, to investigate in detail correlations and structure beyond the driplines. New neutron detector systems such as the NEXT array integrated within new decay arrays such as the FDS [FDS], and combined spectroscopy capabilities which will be enabled at the HRS [HRS] with GRETA [GRETA] and MoNA-LISA, offer great discovery potential. This will be enhanced by advanced targetry allowing a maximized luminosity for experiments. However, it is the intense FRIB beams, and ultimately the energy upgrade of FRIB400 [FRIB400] that will define how far we can reach.

TOWARDS AND BEYOND THE PROTON DRIPLINE

- The correlations between the momenta of the protons in two-proton decay give information on the nuclear structure. While correlations for light $2p$ emitters have been measured with high statistics, heavier longer-lived radioactive emitters have typically been observed with just a handful of events. With FRIB beams and sensitive TPCs, the correlations for the known $2p$ emitters ^{45}Fe , ^{48}Ni , ^{54}Zn , ^{67}Kr can be measured with thousands of events and new $2p$ emitters can be discovered.
- The region around ^{100}Sn , the heaviest $N=Z$ doubly magic nucleus, is a crucial reference point for benchmarking theoretical models. The decay of ^{104}Te and ^{108}Xe are expected to elucidate the mechanism of nuclear clustering through super-allowed alpha decay.

- More light nuclei beyond the proton dripline can be discovered and studied. Interest includes the discovery of a six-proton ground-state emitter with ^{20}Si being a good candidate as it can be reached via a $2n$ knockout reaction. Evolution of magic numbers at and beyond the proton dripline may not mirror that seen in their particle-stable neutron rich counterparts due to the influence of the continuum. Measurement of masses and 2^+ excitation energies near ^{22}Si , ^{24}S , ^{34}Ca , and ^{48}Ni can be used to infer if they are as doubly-magic as found for their mirrors.

MAPPING AND UNDERSTANDING THE NEUTRON DRIPLINE

- Future exploration of single and multi-neutron resonances will be facilitated by the construction of next-generation neutron detector array(s) which will provide superior position resolution, and a thick LH_2 target with reaction vertex reconstruction capabilities will augment fragment momentum reconstruction. Goals include finding the challenging ground-state $4n$ emitter ^{38}Ne
- Invariant mass spectroscopy will be able to access unbound states in the most neutron-rich Mg, namely $^{39,40,41}\text{Mg}$, and possibly even beyond
- Multi-step reactions in the thick targets allowed for by the FRIB400 upgrade will enable unprecedented reach to new isotopes at the limit of nuclear existence, extending knowledge of the driplines, reaching to ^{42}Mg and ^{70}Ca
- It will be possible to detect and uniquely identify exotic decay modes, such as correlated $2n$ emission following β decay.

THE LIMITS OF MASS AND CHARGE

- Spectroscopy of heavy ($92 < Z < 104$) and superheavy ($Z \geq 104$) elements is fundamental to developing a comprehensive picture of their structure and probing the predicted heavy Island of Stability. However, the small production cross sections in producing these isotopes have hampered progress. Improvements in both beam delivery and detectors will enable progress in this area, as will multi-user capabilities to enable longer experiment running times at the ATLAS facility with AGFA and Gammasphere.
- Developments in ion-source efficiency and upgrades to the target system of the BGS at LBNL will enable a search for element 120, revitalizing U.S. leadership in SHE discovery science.

2.1.6 EVOLUTION OF NUCLEAR STRUCTURE - SHELLS, SHAPES AND COLLECTIVITY

FRIB also offers new opportunities in pushing our exploration of shell evolution much further than we've previously been able to reach. In addition, new facilities, such as the nuCARIBU, open unique avenues in the exploration of specific regions of the nuclear chart. The prospects for significant steps forward in our understanding are excellent, for example, insight will be gained on the residual nuclear interaction and its universal influence on single-particle nucleon structure or the required conditions for more exotic kinds of nuclear deformations.

CHANGING MAGIC NUMBERS

- A particularly exciting region on the nuclear chart is the one around ^{78}Ni where a new island of inversion is predicted, with shape coexistence and a broken-down $N=50$ magic number. The first 2^+ state of predicted collective nuclide ^{76}Fe at $N=50$ can be discovered at FRIB. Spectroscopy beyond the first excited state in a $^{77}\text{Co}(p,2p)$ reaction and studies of its collectivity via (p,p') will only be possible with the energies from FRIB400 and an extended proton target inside GRETA at the HRS. Within the same region of the nuclear

chart, complementary studies for the signatures of shape coexistence including E0 transitions and isomeric states will be possible with the FDS.

- The region of the chart around ^{100}Sn and ^{132}Sn will be accessible for decay and reaction studies, opening opportunities to perform high-resolution studies of the evolution of single-particle states near these two doubly-magic systems.
- Systematic exploration of the single-particle (and collective, pairing) degree of freedom along fixed Z or N numbers moving towards ^{60}Ca and ^{78}Ni , below ^{208}Pb , and along the $N = Z$ line, will provide stringent tests of theoretical models. Systematic measurements exploring different reaction channels are invaluable as they put stronger constraints on the relevant effective interactions, significantly reducing uncertainties. The properties of many of these nuclei are also important in understanding specific aspects of stellar nucleosynthesis.

THE INTERSECTION OF STRUCTURE AND REACTIONS

- It will be possible to obtain the body of data necessary for understanding the open problem surrounding the varying trends in the quenching of single-particle states as observed by either transfer / quasi-free knockout reactions compared to data from knockout reactions on composite targets.
- Direct reactions, including for the purpose of surrogates to determine (n,γ) cross sections on rare isotopes, and in particular transfers with large negative Q values will become possible at FRIB's ReA facility once the beam energies exceed 10 MeV/u. A large-acceptance spectrometer such as ISLA [ISLA] will be critical to enable recoil detection at FRIB's anticipated intensities.

PEAR-SHAPED NUCLEI

- With the coming online of the nuCARIBU facility, Coulomb excitation measurements with either GRETA or Gammasphere will be possible, elucidating shapes of neutron-rich nuclei in the $A \sim 80$ to $A \sim 150$ region. With the expected higher beam intensities, a renaissance in the study of octupole collectivity in Ba-Ce isotopes ($A \sim 145$) will ensue and the probing of single-particle states around ^{132}Sn will become possible.
- Understanding the single-particle structure of the relevant parity-doublet states in the odd- A octupole deformed EDM candidate nuclei (e.g. ^{223}Ra) can be performed at high-resolution magnetic spectrographs. Target developments using highly enriched actinide isotope material will be necessary, but such studies, possibly to be performed at ARUNA laboratories, will complement detailed spectroscopy studies at FRIB and ANL.
- Octupole-deformed EDM candidate nuclei can be directly produced in the fragmentation of U beam at FRIB and used for experiments or harvested for EDM measurements.

AND BEYOND...

- Very neutron-rich systems, such as ^{86}Ni – predicted to have a neutron skin thicker than 0.5 fm – come into reach for scattering experiments with FRIB400, offering perhaps the closest opportunity to studying very neutron-rich matter in the laboratory.
- FRIB400 also opens unique opportunities for fission studies. Due to the enhanced kinematic focusing, many more correlated fission-fragment pairs from very-neutron rich fissioning systems, populated via direct reactions, can enter the HRS focal plane simultaneously, allowing for unmatched correlation studies in coincidence with γ -ray spectroscopy.
- Isotopic chains exhibiting exotic phenomena such as haloes, e.g. C and Mg isotopic chains, are of particular interest as they can inform us on the role of clusterized structures and their description in models.

2.1.7 PRECISION MEASUREMENTS IN THE NUCLEAR SYSTEM

Precision measurements will continue to provide a key testing ground for different nuclear theories, from mass models extrapolating beyond our current knowledge to make predictions for astrophysical processes, to *ab-initio* calculations predicting radii and electromagnetic moments. With increasingly sensitive detection systems and technical advancements, the realm of precision experiments is poised for impactful measurements across the nuclear chart before 2030.

- Nuclear ground and isomeric-state magnetic-dipole and electric-quadrupole moments, spin, and charge radii can all be determined by applying laser spectroscopic techniques to the study of radioactive isotopes. These observables are sensitive to the details of the nuclear wavefunction and the nuclear deformation and are one of the best probes to benchmark modern theories. Future measurements at the BECOLA/RISE facility at FRIB will target nuclei approaching the nucleon driplines and doubly-magic nuclei such as ^{78}Ni , ^{80}Zr , and ^{100}Sn . The FRIB400 upgrade will also benefit these experiments, as it will provide higher rates and a wider reach for the desired isotopes.
- Experiments at ANL will similarly make use of developments with nuCARIBU and the $N=126$ factory to help map the mass surface and measure radii in as-of-yet unexplored regions of the nuclear chart.
- The symmetry energy of the nuclear equation of state can be determined from the difference of mirror charge radii, which can be precisely determined through laser spectroscopy. These types of measurements can provide valuable input needed to interpret the properties of neutron stars.
- Laser spectroscopy techniques offer unique access to the nuclear charge radii of short-lived isotopes far from stability. These techniques have been used to determine how the size of atomic nuclei vary with proton and neutron numbers, providing essential guidance for developing nuclear theory and understanding the evolution of nuclear structure at the extremes of existence. For example, measurement of the Ca radii which has produced high-profile results in the last several years can be extended toward ^{60}Ca , providing a stringent test of theory.
- Experiments with molecules can be engineered to enhance the sensitivity to certain nuclear phenomena and therefore have opened up new opportunities for precision studies of the nuclear electroweak structure and astrophysical signatures. Recent developments have enabled the production of molecules that incorporate certain short-lived radioisotopes in them.
- High-precision techniques are also needed to identify the radioisotopes that are best suited for searches for CP-violating moments. The measurement of P,T-violating moments such as the electric dipole moment (EDM) or the magnetic quadrupole moment (MQM) can serve as sensitive probes for new sources of CP violation. These moments can be enhanced by orders of magnitude for certain nuclei with quadrupole and octupole deformations. While calculated deformation parameters indicate that numerous heavy isotopes may have significant enhancements for new physics, a detailed experimental campaign needs to be carried out to firmly establish (i) the energy differences between the ground-state parity doublets and (ii) the magnitude and character of the octupole deformation. Isotopes such as ^{229}Pa and ^{225}Ra are of particular interest for these studies as they show great promise for enormously increased sensitivity to new physics.

2.1.8 NUCLEAR STRUCTURE TO ASTROPHYSICS

Looking forward, astrophysics and nuclear structure and reactions remain intimately coupled. As has been the case for decades, nuclear structure studies of all types will continue to identify specific nuclear states relevant in specific astrophysically important reactions and constrain the theories which make predictions beyond our experimental reach, for example. And experiments targeting statistical aspects of nuclear structure, and unique cases of isomers relevant for explosive nucleosynthesis will similarly be pursued in response to sensitivity studies which help target such efforts.

NUCLEAR EQUATION OF STATE

- Higher sensitivity to the slope of the symmetry energy using the difference in charge radii of mirror pairs method could be obtained with larger $|N-Z|$ values. Charge radii for the pairs ^{22}Si - ^{22}O , ^{52}Ni - ^{52}Cr and ^{50}Ni - ^{50}Ti can be measured with collinear-laser spectroscopy at FRIB.
- Future measurements of dissipative collisions at FRIB and FRIB400 can study the EOS from pion production and elliptical flow measurements. Only with FRIB400, the important density of $2\rho_0$, which is critical for understanding nuclear matter in neutron stars can be reached. Initial studies can be performed with the AT-TPC inside SOLARIS with fast beams for FRIB. Later, the $S\pi$ RIT TPC can be used inside of the HRS dipole and coupled to the next-generation LANA neutron detector.

BIBLIOGRAPHY

[ARUNA] [ARUNA: Advancing Science, Educating Scientists, Delivering for Society](#). Whitepaper authored by the ARUNA community (2022).

[FDS] [FRIB Decay Station](#)

[FRIB400] [FRIB400 – The Scientific Case for the 400 MeV/u Energy Upgrade of FRIB](#). Whitepaper authored by the FRIB Science Community (2019).

[GRETA] [The Gamma-Ray Energy Tracking Array GRETA](#). Whitepaper submitted to the Nuclear Astrophysics and Low Energy Nuclear Physics Town Meeting August 2014 (2014).

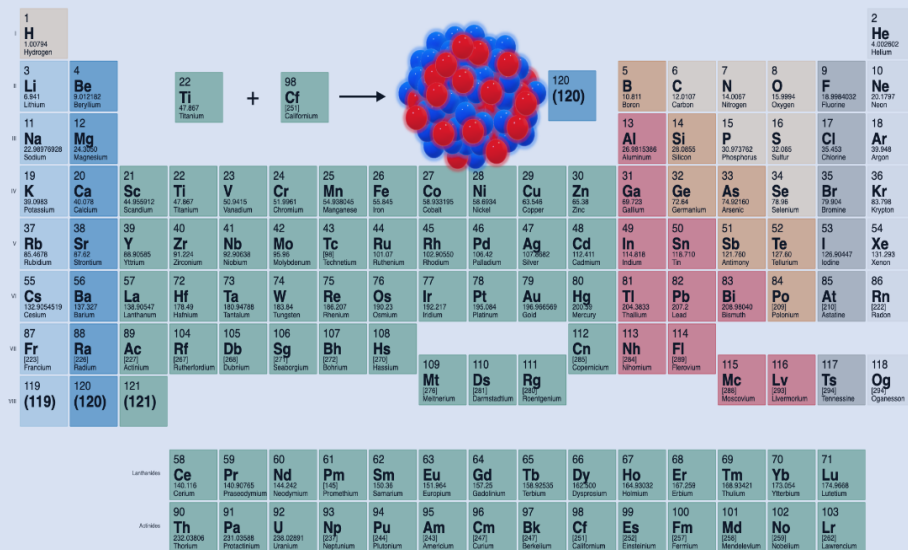
[HRS] [HRS – A high rigidity spectrometer for FRIB](#). Whitepaper authored by the nuclear science community (2017).

[ISLA] [ISLA – A Recoil Separator for ReA12](#)

[SHE] [The Status and Ambitions of the US Heavy Element Program](#). Whitepaper authored by the heavy element working group (2022).

SUPERHEAVY ELEMENTS: THE MAMMOTHS OF THE NUCLEAR CHART

Extending the Periodic Table of elements remains a compelling scientific endeavor. Since the last NSAC Long Range Plan in 2015, four new elements with atomic numbers (Z) 113, 115, 117, and 118 were added to the Table - Nihonium (Nh), Moscovium (Mc), Tennessine (Ts), and Oganesson (Og) respectively. Whether these massive elements continue to obey the organizing principle of the Table – which sorts the lighter elements into the familiar groups with recognizable recurring patterns of chemical reactivity – remains a central question in chemistry, while determining the limits of nuclear mass and charge is the domain of nuclear physics.



Attempts to synthesize elements with $Z=119$ and $Z=120$ have begun and will push the current technology. In the United States the 88-Inch Cyclotron at LBNL is the facility likely best suited to attempt a new-element search, since the experiment involves long periods of running intense beams (\sim particle μ A of ^{50}Ti) on actinide targets, such as Cf (produced, uniquely, at the HIFR at ORNL), in order to approach the minuscule (fb) production cross sections. However, there are other facilities, including those at TAMU and ANL, which have dedicated heavy-element programs – combining the various capabilities, the community of US scientists can address fundamental questions in heavy-element science.

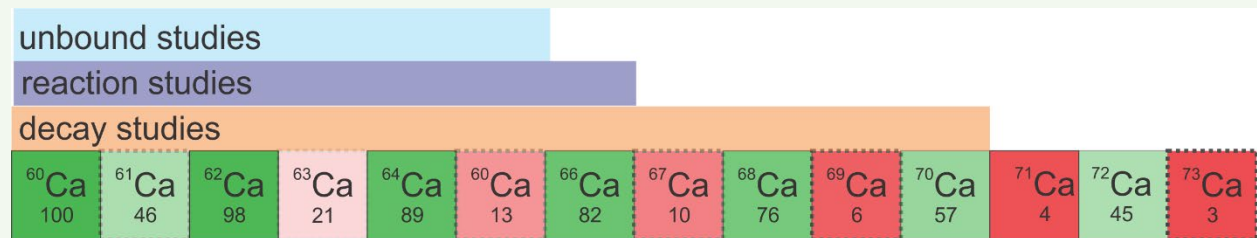
Initial discovery experiments can provide first structure information on basic properties, such as the lifetime and ground-state decay modes. Another approach is to perform detailed spectroscopic studies of deformed nuclei in the vicinity $Z\approx 100$ and $N\approx 152$. These experiments are easier but test the same models that make predictions for super heavy nuclei. One can learn about the single-particle structure, pairing, shapes, and elementary excitation modes of these very heavy nuclei. Perhaps most importantly, as it ultimately determines whether a nucleus can exist, the variation of quantum shell corrections and the robustness to fission, can be investigated.

Experiments on the atomic and chemical properties of the heaviest elements are similarly challenging and can only be performed one-atom-at-a-time. A look at the Periodic Table in the figure indicates that there are several known elements (those vertically displaced downward from the seventh row) for which there is no atomic structure or chemical information – this can change soon. Gas-phase chemistry, and even chemistry in the aqueous phase, is possible at the required level of sensitivity. Such types of experiments will quickly tell us if the iconic Periodic Table needs revision.

EXTREME EVOLUTION ON THE NUCLEAR CHART: ^{60}Ca AND BEYOND

Defining the edges of the nuclear chart bounded by the nucleon driplines is a fundamental benchmark for modeling nuclear binding, places a fundamental limit on astrophysical processes, and is a playground of exploration for new phenomena that can occur in open quantum systems. Since the last Long Range Plan, the identification of the neutron dripline has been accomplished up to a $Z=10$. FRIB400 will be needed to push knowledge of the neutron dripline up the nuclear chart to perhaps $Z\sim 60$. Within this range, the elemental chains of Ca, Ni, and Sn will be key experimental signposts pointing the way to improved understanding of atomic nuclear systems.

The probability of existence in percent for the neutron-rich Ca isotopes beyond ^{60}Ca is presented in the figure below. The recent observation of a bound ^{60}Ca suggests that the theoretical modeling may be accurate and the dripline for the Ca isotopes may indeed extend to ^{70}Ca , the last isotope with a 50% probability of existence.



Probing ^{70}Ca would be near the limit of production capabilities even at FRIB400 but, if bound, studies of ^{70}Ca would provide not only knowledge of its existence but first information on gross structural properties through a measurement of the nuclear half-life and potentially beta-delayed neutron emission probabilities. Adding to this, the detailed studies which will be enabled in the lighter Ca isotopes between our current reach of $N\approx 34-36$ and $N\approx 50$, will allow a mapping of the relative energies of neutron single-particle orbitals with increasing neutron excess, and provide a further test of theory. Nucleon knockout and charge exchange will be enabled with GRETA and the HRS, while multi-modal decay spectroscopy will be possible at the FRIB Decay Station.

3 CONNECTING NUCLEI TO THE COSMOS

A confluence of breakthroughs in multi-messenger astronomy, laboratory nuclear physics, and computational modeling of both nuclei and the extreme astrophysical environments where they react, has propelled nuclear astrophysics to the forefront of science. These breakthroughs provide extraordinary opportunities for nuclear science – working together with astronomers, geo-chemists, and experts in other fields - to address long-standing fundamental questions about the cosmos: What were the first elements created after the Big Bang? What is the origin of the heavy elements? What signatures do stars leave behind in the chemical elements and stellar remnants (white dwarfs, neutron stars, and black holes)? What is the nature of matter under extreme conditions? What do the multi-messenger signals from transient events such as neutron star mergers, supernovae, novae, and X-ray bursts tell us about physics at the most extreme conditions encountered anywhere in the Universe?

The first gravitational wave observations from compact object mergers represent an incredible advance in observational astronomy and have led directly to improvements in our understanding of nuclear matter. New detectors for cosmic neutrinos, an upcoming MeV-scale gamma-ray mission, new X-ray telescopes, new optical telescopes with unprecedented time domain coverage, new capabilities to analyze stardust, and the advent of asteroseismology are likely to bring similar advances for nuclear astrophysics. Nuclear physics plays an essential role in the extreme astrophysical environments encountered in the majority of targets for this new era of multi-messenger astronomy. Indeed, one of the main motivations for next generation, high frequency gravitational wave observatories is the nuclear physics of neutron stars. A different kind of messenger that drives an increased need for nuclear physics is stellar spectroscopy. While stellar spectroscopy has a long history, efforts are now reaching a scale where a detailed map of the evolution of the elemental composition of the Galaxy over its entire history is emerging. Analysis of this “fossil record” of chemical evolution is revolutionizing nuclear astrophysics, pointing to a new, unanticipated diversity of nucleosynthetic processes.

In parallel, advances in experimental nuclear physics are poised to address the dramatically increased need to understand the underlying nuclear physics of stars, stellar explosions, and element synthesis. These advances include a new generation of revolutionary rare isotope beam facilities, in particular the long-awaited FRIB and the forthcoming novel beam production upgrades at ATLAS, underground accelerator laboratories, and a whole suite of major developments at a broad range of above-ground accelerator facilities providing charged particle, gamma, and neutron beams. This creates unprecedented opportunities to address long-standing nuclear physics challenges in astrophysics: to study the properties and reactions of unstable nuclei made in stellar explosions, to understand the physics of nuclear reactions at extremely low energies and cross sections, and to probe nuclear physics at extreme densities in the laboratory.

Simultaneously, the rise of exascale computational facilities, and support for the development of nuclear astrophysics codes that can take advantage of them, are beginning to enable computational modeling of astrophysical environments that achieve sufficient fidelity to adequately include the key nuclear processes. This is especially true for the many multi-messenger sites where three-dimensional simulations have turned out to be essential, such as neutron star mergers or supernovae. These simulations are key to understanding the origin of the elements, making clear the nuclear reactions that govern these events, and providing the essential link between nuclear physics and the astronomical observables. In parallel, exascale computations of nuclear structure and nuclear reactions are providing data for these simulations that remain inaccessible to experiment.

The synergy of these developments in nuclear physics, astronomy, and computing put nuclear science and nuclear astrophysics at a special point in time, with a new understanding of the nuclear processes that shape the visible

universe within our grasp. To take advantage of this opportunity, full support of the extraordinarily broad range of required technical capabilities and developments in experiment, theory, and computational modeling is essential. This requires supporting the correspondingly broad range of research groups at national laboratories, user facilities, and universities needed to address this multi-physics challenge. Centers will play an important role in creating the connections between these different areas. Of particular importance for nuclear astrophysics will be interdisciplinary centers and networks that span nuclear experiment, nuclear theory, computational physics, astrophysics, astronomical observations, and cosmochemistry to facilitate and drive national and international collaborations, the timely exchange of ideas and data, and build the interdisciplinary communities for the multi-messenger era in nuclear astrophysics.

Low energy nuclear astrophysics relies heavily on other areas in nuclear science. Experimental advances in nuclear structure and nuclear reactions, discussed in Section 2 of this white paper, directly impact nuclear astrophysics and are often reflected in astronomical observables. A predictive theory of nuclei across the entire chart of nuclides, as discussed in Section 1, is a major goal of the field and is of particular importance for nuclear astrophysics to obtain the broad range of required nuclear data that are beyond the reach of experiments. Neutrinos and their fundamental properties (see white paper [WP_NFS]) play a pivotal role in many astrophysical scenarios and are interlinked with nuclear processes and nucleosynthesis outcomes. The properties of dense nuclear matter are a major theme in low energy nuclear astrophysics and pertain directly to questions of hot and cold QCD (see white paper [WP_QCD]). By taking these advances in other areas of nuclear physics and exploring their cosmic consequences, advances in nuclear astrophysics will also provide nuclear science with a broad impact on other fields such as astronomy, astrobiology, planetary science, and dark matter physics.

MAJOR ACCOMPLISHMENTS

Nuclear astrophysics traces its history to the suggestion in the 1920s that the Sun and other stars are nuclear powered, with the subsequent emergence of a first comprehensive theory of the origin of the elements in the 1950s and the birth of experimental nuclear astrophysics in the 1960s. The last decade has seen progress in nuclear astrophysics that is unparalleled since the 1950s.

New successful measurements of key nuclear reactions in stars, in combination with progress in reaction theory and stellar models, had very broad impacts on the field. This includes understanding the onset of nucleosynthesis in the first stars, which is revealed in the present day by observations of the composition of the oldest surviving stars in the Galaxy. It includes an expanded understanding of the interior of the Sun through improved measurements of the reactions in the CNO cycle, in combination with the first detection of solar neutrinos from this cycle. The influence of nearby supernova explosions on the solar system was revealed by combining laboratory data and theoretical calculations on nuclear reaction rates producing ^{60}Fe and ^{239}Pu , supernova nucleosynthesis models, and the detection of these long-lived radioactive isotopes in meteorites, deep sea sediments, and moon rocks. Decades of community effort to constrain extremely slow stellar reaction rates were key to interpreting novel asteroseismology data on the interior composition of white dwarves and the black hole mass distribution, which was revealed by LIGO gravitational wave observations and included a surprising number of very massive stellar black holes. The measurements at the heart of these efforts were enabled by a sustained effort at a broad range of university and national accelerator laboratories, taking advantage of advanced detection techniques or underground approaches. The simulations that reveal the inner lives of these events were facilitated by networks of experts in diverse areas of nuclear theory and other fields.

The most dramatic and impactful recent astronomical event for nuclear astrophysics was the multi-messenger observation of the gravitational wave event GW170817, which provided proof that short γ -ray bursts are the result of neutron star mergers. Observations of the optical afterglow marked the first direct observation of a site of the rapid neutron capture process (r-process), opening a pathway to address one of the most important open questions in the field, the origin of the heavy elements. The ability to accurately model the r-process powered light curve of this kilonova was a triumph for the field, and has triggered unprecedented progress in computational modeling of these events, which in turn has revealed an unanticipated diversity of outflows and nucleosynthesis sites within the merger event with different weak and strong r-process signatures. At the same time, various observational hints, such as the rates of observed neutron star mergers, leave open the possibility that mergers are not the only r-process site. Our ability to simulate the nucleosynthesis outcome of a merger has been enhanced by advanced rare isotope beam facilities such as NSCL, CARIBU, and more recently, taking advantage of international collaborations, with RIKEN, which have succeeded in the past decade to measure the properties of a broad range of the extremely neutron-rich nuclei in the r-process, in particular most of the nuclei participating in the weak r-process. This has enabled relatively reliable predictions of the r-process nucleosynthesis of the lighter heavy elements, though reaction uncertainties remain to be addressed.

The diversity of heavy element nucleosynthesis sites was further increased by evidence for a continuum of neutron capture processes operating in our Galaxy, including intermediate neutron capture processes (i-processes). This evidence was provided by a combination of laboratory measurements of neutron generating and neutron capture reactions, in particular $^{13}\text{C}(\alpha, n)$ and $^{22}\text{Ne}(\alpha, n)$, and the neutron capture reactions in the slow neutron capture process; advances in modeling of stars that transcend the traditional spherical stellar burning shell structure to explore the three dimensional nature of these shells; laboratory analysis of stardust; and a dramatic increase in stellar spectroscopy data that has now begun to provide a detailed and increasingly complete map of the chemical evolution of the Galaxy. Taken together, a much more complex, and presumably much more complete, picture of heavy element nucleosynthesis is now emerging that has resulted in a paradigm shift and a whole new range of open questions.

Advances in laboratory measurements of stable and radioactive beam reactions, in combination with advances in computational modeling, have also led to tremendous progress in understanding other nuclear-powered stellar explosions. A sustained effort at a diverse range of stable and radioactive beam facilities have made classical novae the first astrophysical site where the majority of nuclear reactions are informed by direct measurements at the relevant astrophysical energies. In parallel, multi-dimensional simulations have revealed the origins of the mixing of white dwarf and accreted material which characterizes nova ejecta. A broader effort, again combining radioactive beam and stable beam accelerator facilities, has now addressed some of the key nuclear physics related to neutron deficient unstable nuclei in the rp-process that powers X-ray bursts. This has led to a transition from attempts to understand basic phenomenology to comparisons of detailed models with precision observations of specific X-ray binary systems to extract neutron star properties and other system parameters. Here too, multi-dimensional simulations are teaching us how the explosion develops and spreads across the surface of the neutron star, revealing features that will be essential to extend such observational analysis to the majority of systems. After decades of effort, which often produced more failures than explosions, modeling of core collapse supernovae now qualitatively reproduce the basic observations of the explosion energy and ejected mass of radioactive nickel. This progress has relied on three-dimensional modeling, utilizing world-class computing resources, as well as better understanding of the nuclear equation of state and the weak nuclear reactions that drive the collapse of the stellar core. This last achievement has required advances in nuclear structure calculations calibrated by measurements of charge exchange reactions in the increasingly neutron-rich nuclei that dominate the composition of the collapsing stellar

core. Simulations of thermonuclear supernovae, challenged by observations, have made tremendous progress on reconciling progenitor scenarios and observable outcomes. However, all of this work is predicated on the still uncertain rate of carbon-carbon fusion, the target of ongoing experimental programs employing a variety of methods [AL122].

Unprecedented progress has also been achieved in the understanding of the dense matter equation of state that governs the properties of neutron stars. While laboratory heavy ion collision experiments have provided much refined constraints, these have now been complemented with a much-expanded range of additional new constraints: LIGO gravitational wave signals from neutron star mergers, parity violating electron scattering experiments at Jefferson Laboratory, effective field theory with uncertainty quantification, and observations of X-ray pulsar light curves with the ISS based NICER observatory. As a consequence, significant progress has been made in constraining the nuclear matter equation of state, including the symmetry energy, particularly below and near saturation density. Going beyond that to cover and better constrain the entire density range of importance of nuclear astrophysics will be the challenge for the future.

THEORETICAL NUCLEAR ASTROPHYSICS PROGRESS

The past decade has seen tremendous progress in theoretical nuclear astrophysics, supported by the availability of increasing computational resources and improvements in the included nuclear physics provided by progress in nuclear astrophysics experiments and nuclear theory and tested by new and improved astronomical observations. Achieving this progress, across the range of astrophysical scenarios and nucleosynthesis sites, has required collaborations among a diversity of domain experts, both from within nuclear physics and outside.

NEUTRON STAR MERGERS: Neutron star merger (NSM) simulations in full general relativity, including nuclear-theory based equations of state and approximate neutrino transport have become possible in the past decade. Numerical relativity simulations in the last decade were key to develop and validate the theoretical waveform models used to interpret GW170817 and constrain the tidal deformability of neutron stars. Simulations have also revolutionized our understanding of mass ejection and nucleosynthesis from these systems. The amount of tidally stripped material ejected in mergers was found to be significantly smaller than what was anticipated on the basis of Newtonian calculations. Instead, the outflows were found to be dominated by shocks as well as neutrino- and magnetically-driven outflows on different timescales. Neutrino irradiation was discovered to play a crucial role in setting the composition of these components of the outflows, producing a mix of light and heavy r-process elements, as spectacularly confirmed by the blue kilonova in GW170817. We also learned that the post-merger dynamics, which depends sensitively on the equation of state of matter at extreme densities, are imprinted in the properties of the outflow and, consequently, in the emerging kilonova radiation. This, in turn, enabled the creation of multi-messenger pipelines to constrain the nature of dense matter and the origin of the r-process elements.

R-PROCESS: 2022 marked the 65th birthday of the first paper theorizing the rapid neutron capture process, by Burbidge, Burbidge, Fowler, and Hoyle. In this seminal work, the r-process showed itself in the solar abundance distribution via the location of ‘peaks’ at $A \sim 80, 130, 195$ (the so-called first, second and third r-process peaks) due to neutron shell closures at $N=50, 82, 126$. Subsequent observations of chemical evolution have pointed to the need for a rare r-process site. The neutron star merger GW170817 gave the r-process community its first real-time event. The early blue emission suggested the presence of ‘weak’ r-process elements (between the first and second peaks) and the observed spectra further supported this picture by suggesting a strontium absorption feature. Infrared emission after a few days served as a strong indicator of high opacity elements, implying the production of at least

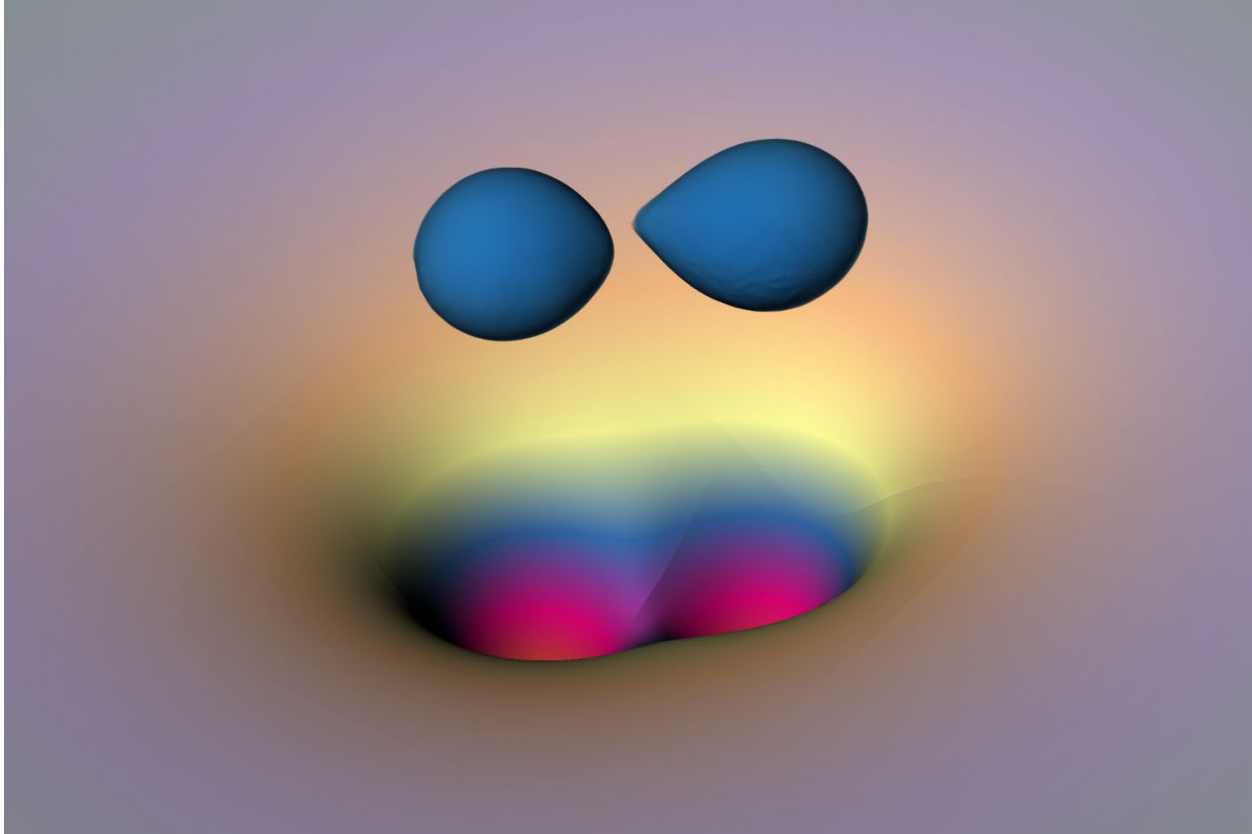


Figure 3.1: Numerical relativity simulation of tidally interacting neutron stars shortly before merger. The elevation plot at the bottom of the figure shows the lapse function, which corresponds to the Newtonian gravitational potential of the stars in the classical limit.

lanthanides (between the second and third peaks), but leaving it unclear as to whether heavier elements such as gold and actinides were produced. Beyond localizations that enable electromagnetic follow-up of individual events, LIGO is also measuring the binary neutron star merger rate. Following GW170817, galactic chemical evolution studies compared the merger rate reported to the merger rate needed in order to account for all the europium, a common marker for the main r-process, in our galaxy. Although abundance uncertainties currently limit our ability to make firm conclusions, that we are now comparing directly with data exemplifies the new era that r-process studies have entered [Cow21].

Although there is tremendous excitement in the r-process community regarding neutron star mergers, the past decade has also seen progress in exploring the role of other r-process candidate sites, such as core-collapse supernovae, rare magneto-rotationally driven (MHD) supernovae, and collapsars. Recent work has demonstrated that r-process conditions are not found in most modern core-collapse supernova simulations, however other nucleosynthesis processes at play in these environments could synthesize nuclei up to $A \sim 100$. Recent work on collapsars suggests that although they are rarer than neutron star mergers, they could eject more r-process material in each event. However, while some simulations find a strong r-process, others only find a weak r-process (not reaching the lanthanide elements). Work over the last years on MHD-driven supernovae has demonstrated that the ejecta could undergo a full r-process (reaching third peak elements) due to the stronger magnetic field freeing more neutron-rich material from the surface of the neutron star. For all of these prospective r-process sites, the treatment

of neutrinos impacts predictions for how heavy of nuclei the synthesis can reach, thereby influencing our understanding of their contributions to the galactic inventory of elements and demanding higher fidelity simulations.

Predictions for r-process observables are not only sensitive to the hydrodynamic modeling, but also to the physics of the nucleosynthesis itself. Progress has been made to identify and address both theoretical and experimental nuclear physics inputs of relevance [Mum16]. Some prime examples of new results that recently had impact in r-process studies include: mass measurements of neutron-rich lanthanides via the Canadian Penning Trap (CPT) at Argonne National Laboratory, measurements of the beta-decay properties of lanthanide species at BRIKEN, new global beta-decay predictions, and new calculations for the fission yields of very neutron-rich nuclei. There has also been much progress to parse out the influence of individual processes and nuclei. Following GW170817, it was realized that the isotope ^{254}Cf could serve as a beacon of actinide production in mergers due to its high spontaneous fission Q-value, potentially producing a bump in the kilonova light curve. MeV gammas associated with a merger have also been shown to be influenced by whether fissioning species are produced. Additionally the impact of nuclear isomers on the light curve has begun to be explored.

STELLAR/SOLAR EVOLUTION: The evolution of stars is one of the foundations of nuclear astrophysics. Stars are responsible for the synthesis of the majority of nuclei beyond helium and for the elements up to iron that often serve as seed for the synthesis of heavier elements. They also synthesize about half of the heavy elements via multiple slow and possibly intermediate neutron capture processes, and define the progenitors for subsequent stellar explosions such as thermonuclear or core collapse supernovae. Combined advances in experiments determining the extremely slow nuclear reaction rates in stars, new observations such as seismology of white dwarfs and black hole mass distributions from LIGO gravitational wave observations, as well as advanced models of the complete stellar evolution sequence are now probing stellar evolution in unprecedented detail and have revealed inconsistencies that may point to fundamental issues in our understanding of low energy nuclear reactions, or stellar models, or both. Observations of extremely old stars have provided first glimpses at nucleosynthesis in the very first stars that can be compared to models of such stars. The recent observation of neutrinos from the CNO cycle in the Sun by BOREXINO and the success of solar models with new precise nuclear reaction information have been another major milestone. Multi-D computer simulations of specific stellar evolution stages have become possible as well and have led to major new findings, for example that hydrogen ingestion can lead to novel nucleosynthesis such as the i-process, and that 3D effects such as the merging of burning shells or turbulence in late stellar burning stages can have significant impact on core collapse supernova models. Another major step for the field were the calculations of complete nucleosynthesis models of large-scale grids of stars spanning the entire mass and metallicity range, that provide together with chemical evolution models of Galaxies, predictions of the entire chemical enrichment history of the galaxy that can be compared to data from large scale stellar spectroscopy. The results are promising for many elements, but also reveal deficiencies in the understanding of stellar nucleosynthesis.

CORE-COLLAPSE SN: In the past decade, self-consistent simulations of core-collapse supernovae (CCSNe) have advanced to qualitative agreement with basic observations like the explosion energy and amount of radioactive ^{56}Ni created, first in axisymmetry (2D) and later in full three dimensions. In the process, we discovered that the central engine of the supernova, powered by material accreting on to the newly-formed neutron star, remains operative for several seconds, much longer than was thought in the past. This hard-won agreement depends on spectral neutrino radiation transport, to correctly predict the neutrino heating that drives the revival of the stalled supernova shock and multi-dimensional hydrodynamics to correctly capture the complex fluid motions that occur in response to this heating. At the nuclear scale, the success of these simulations has also depended on our improving understanding of the nuclear equation of state and interactions between neutrinos and nuclei or nuclear matter. The past decade

has also seen considerable improvements in the treatment of the isotopic composition of the ejecta, allowing better determinations of isotopic yields and better, more detailed, constraints from astronomical observations. This has included as many as 160 isotopes evolved within the neutrino radiation hydrodynamic simulation. The large number of species is necessary since CCSN contribute to the Galactic abundance of a wide variety of intermediate and iron peak nuclei, as well as potentially the νp -process, γ -process and weak r -process. Furthermore, state-of-the-art models are now being extended beyond the seconds where the neutrino heating powers the explosion, through the hours it takes for the supernova shock wave and the newly made isotopes to travel to the surface of the star and become observable by telescopes.

THERMONUCLEAR SUPERNOVAE: Key observational advances have spurred theoretical work on thermonuclear supernovae and other white dwarf transients over the past decade. Perhaps the most significant of these observational advances was the discovery of three hypervelocity white dwarfs in the Gaia DR3 data catalog, thought to represent the surviving binary companions of exploded white dwarfs, supporting the “dynamically driven double-degenerate double-detonation” or D6 scenario for Type Ia supernovae. Current state-of-the-art hydrodynamic simulations are now able to model the merger of binary white dwarfs, including the thin helium layers that are vitally important to the D6 mechanism, and including inline nuclear reaction networks of up to 50 isotopes, significantly larger and more computationally expensive than the 19 isotope α -capture network that has been the workhorse of thermonuclear transient models for decades. An additional critical theoretical advance has been in the synthetic radiative transfer computed from hydrodynamic models. Recent work has shown that accurate calculations of the synthetic spectra and light curves beyond 15 days requires the inclusion of non-local thermodynamic equilibrium (NLTE) effects. NLTE radiative transfer is computationally expensive, and undertaking the multidimensional radiative transfer calculations, which are vitally important to connect models to observations at times beyond 15 days, will be a major challenge for the coming decade.

NOVAE: For novae, multi-dimensional simulations of the simmering phase, before the thermonuclear runaway, have revealed a natural mechanism for mixing of carbon- and oxygen-rich material from the white dwarf into the accreted envelope on the surface of the star. This solves a long-standing puzzle, where observations reveal that as much as 50% of the ejecta is not accreted material, but rather material from the white dwarf. This mixing of carbon and oxygen, which catalyze the CNO cycle for hydrogen burning, is essential to match the observed energetics of novae, but models of the past were forced to simply assume the mixing occurred. Recent models for novae have also increased their range of isotopic influence, suggesting that lithium is also produced in sufficient quantities to influence Galactic chemical evolution. This suggestion seems to be supported by spectral observations of nova outbursts.

NEUTRON STAR TRANSIENTS: X-ray bursts result from the thermonuclear burning of a thin fuel layer on the surface of a neutron star. Observations of low mass X-ray binaries allow us to follow multiple bursts from a single source, and in some cases, use the properties of the light curve to infer the neutron star mass and radius, helping to constrain the nuclear equation of state. Observational evidence suggests that the ignition of the burning front begins locally and spreads across the surface of the neutron star. In the past decade, multidimensional simulations have begun to examine the detail of the burning front propagation and thermal transport across the neutron star surface. To get accurate predictions of the nucleosynthesis, large networks and spatial resolutions that resolve the burning front are needed, and these calculations are beginning, leveraging the large speed-ups attained by GPUs on leadership computing systems.

NEUTRINO OSCILLATIONS: A rich variety of nonlinear neutrino flavor-changing phenomena have been identified in the context of core-collapse supernovae and neutron star mergers. Most notable are the matter-neutrino resonance,

the fast flavor instability, and collisional instabilities, which occur deep within the dynamical regions of these events and have the potential to significantly affect the isotopic composition of the ejecta in supernovae and mergers. The full evolution equations for flavor-changing neutrino distributions have been established at the mean-field level of approximation, including effects of wavepacket decoherence, helicity/pair coherence, and collisional processes. Many-body flavor transformation calculations have been extended to thousands of neutrinos, establishing certain regimes in which the mean-field equations are a good approximation to the full many-body treatment. Although a complete treatment of neutrino flavor in global simulations remains computationally prohibitive, effective treatments have established that the results of supernova and merger simulations can be significantly affected by flavor transformation.

PHYSICS OF NEUTRON STARS: The nuclear physics of neutron stars is simultaneously an important topic in nuclear physics in its own right and an essential input to simulations of the births, lives and deaths of neutron stars. Over the past decade, the science of dense matter has been transformed by several observations: (i) the first observation of neutron stars with masses equal to or greater than twice the mass of the sun, (ii) the first observation of gravitational waves from a double neutron star merger, (iii) continued advances in electromagnetic observations of neutron stars, including those from the NICER observatory. On the theory side, chiral effective field theory has transformed our understanding of low-density neutron-rich matter and Bayesian inference has improved our ability to meaningfully interpret the ever-growing neutron star data set. Experiments at rare isotope beam facilities and parity violating experiments at JLab have provided important constraints. During this period, theoretical models have provided new insights about the thermal and transport properties of the solid and superfluid matter encountered in the neutron star crust and have been employed to interpret the thermal evolution of accreting and magnetized neutron stars.

NUCLEAR THEORY FOR ASTROPHYSICS: Nuclear structure and reaction theory is a critical capability that enables much of the progress in nuclear astrophysics simulations. Theory is used to turn direct and indirect measurements into evaluated nuclear data and to predict nuclear properties that cannot be measured. Advances over the past decade have provided nuclear data that is at the core of all current simulations in nuclear astrophysics.

Utilizing improved treatment of nuclear forces and advanced computational capabilities, nuclear theory has provided predictions for increasing numbers of isotopes over the past decade. Complementary (shell model and density functional theory-based) approaches enable the calculation of many nuclear structure properties needed for astrophysical applications. Some of these properties are used directly in simulations, e.g., masses, while others, such as gamma-ray strength functions and level densities, have been incorporated into statistical Hauser-Feshbach reaction calculations which enter simulations as reaction rates. Codes and databases have been developed that enable statistical reaction calculations for nuclear reactions with most isotopes across the isotopic chart. These nuclear data collections have been extensively utilized, not only for predicting astrophysical observables, but also as a baseline for studying sensitivities of observables to nuclear physics input.

For light-ion reactions, *ab initio* approaches are able to treat structure and reactions on equal footing and successfully predict scattering, fusion, and capture cross sections. For direct (non-statistical) reactions with medium-mass and heavy-mass nuclei, important steps have been taken to improve both the reaction descriptions and the requisite nuclear structure input. Optical models, which are key ingredients for both direct and statistical reaction calculations, have seen improvements in terms of microscopic underpinnings and uncertainty quantification. Phenomenological fission calculations have been extended to predict a larger number of observables, are constrained by a broader range of data than ever before, and correlations are being exploited to infer quantities that

cannot be directly measured. Microscopic fission theory has made impressive progress in its ability to predict a broad range of fission properties, with increasing accuracy.

Heavy ion collisions offer the only means of producing, and thus directly studying, nuclear matter far from saturation density on earth. Such extreme matter is found in astrophysical environments (e.g., neutron stars) and thus it is important to study and accurately model. Dynamical transport models provide a microscopic description of the evolution of heavy ion collisions. Interpretation of experimental observables relies on comparison to transport models in order to make contact with the underlying equation of state and the form of the microscopic interaction. A wide variety of transport models exist and within the last few years a significant concerted effort was made to systematically compare predictions of such models leading to confrontation with experimental observables, with pion yield ratios key among them. This is a significant step forward in understanding and further reducing systematic uncertainties in the nuclear equation of state needed to describe neutron stars.

Theory has also been developed to enable indirect measurements of reaction rates that are difficult or impossible to measure directly. Indirect methods, such as the Trojan Horse method for direct reactions and the Surrogate Reactions method for statistical reactions, rely on reaction theory to connect measured data to the desired reaction cross sections. Close collaborations between nuclear theory and experiment have enabled benchmark studies and applications to reactions that have previously been inaccessible.

COMPUTATIONAL PROGRESS: On the practical side, our ability to complete these simulations has relied on the provision of increasing amounts of computing power, now at the exascale, by the agencies which support our research. However, access to the highest performing computers is only the first step toward world-class simulations. The computational apparatus for each problem of importance must be developed to take advantage of these machines and improvements to the included physics that require the additional computing power must be added. Existing codes must be ported to new architectures, new codes with new capabilities must be developed. For all of the simulations mentioned above, the codes that underlie them continue to undergo this process. Entire code bases have been ported to GPUs, gaining order-of-magnitude speed ups compared to CPUs. This additional computational power allows us to use better physics, e.g., larger nuclear reaction networks, and increased resolution, to greatly improve the fidelity of the simulations. In some cases, new improvements developed with one problem in mind also benefit other problems. For example, low Mach number hydrodynamics methods, initially developed for the ignition of flames in Type Ia supernova models, have also been applied to convection in massive stars, the Urca process, and X-ray bursts, with many other potential applications in nuclear astrophysics. Spectral deferred correction methods for coupling physics processes together without operator-splitting errors arose in the applied math community and had early applications to terrestrial combustion. These methods are now being used in astrophysics, and are critical to situations where the nuclear energy release is short compared to the hydrodynamic timescale, such as in astrophysical detonations in Type Ia supernovae. These methods can also reduce the computational complexity of the reaction integration and we expect spectral deferred correction integration to benefit many other explosive environments as well. These developments, both new implementations and new algorithms to harness new hardware, also rely on close collaboration with the community of computational scientists and applied mathematicians, whose expertise has enabled our use of these tremendous computational resources. This is one place where support for cross-disciplinary collaborations has been extremely valuable.

3.1.1 EXPERIMENTAL NUCLEAR ASTROPHYSICS PROGRESS



Figure 3.2: Map showing the university- and laboratory-based accelerator facilities involved in experimental nuclear astrophysics progress since the last Long Range Plan. For clarity, not all institutions involved in nuclear astrophysics research - for example, those without an accelerator laboratory - are shown.

STARS: The first models of stars that included nuclear reactions for energy generation were developed over a century ago. More thorough theories detailed the sequence of stellar burning by the mid-1950s and significant progress in computational modeling of stars has been accomplished since. Despite these successes, our understanding of stars and their explosions is incomplete. As the era of multi-messenger astrophysics begins to mature, both the success of experimental progress, and the shortcomings in the nuclear physics inputs and assumption of spherical symmetry in stellar models have become apparent. Now, high-resolution spectroscopic observations, sophisticated 3-dimensional stellar models, stellar seismology, presolar grain analysis, and neutrino signatures can be coupled with advances in nuclear physics laboratory measurements to elucidate our understanding of the stars.

The fundamental challenge for nuclear physics is to determine nuclear reaction rates at extremely low energies near the reaction threshold [ALI22]. For the charged-particle reactions driving the evolution of stars, rates drop more-than-exponentially with decreasing energy. As a consequence, direct measurements at astrophysical energies have not been possible for many reactions, leading to large reaction rate uncertainties. Nevertheless, impressive progress has been made over the past decade. Advances in available facilities, instruments, and techniques have enabled measurements at extremely low energies as well as high precision measurements at higher energies. Both are critical for guiding theoretical extrapolations into the astrophysical energy regime. New facilities have come online or have been upgraded at FRIB, ATLAS at Argonne, and throughout the ARUNA network [ARUNA22]. Among these are the Sta. Ana accelerator; the CASPAR underground laboratory; the ultra-intense ion beams at LENA-II; new spectrograph facilities at Florida State University, TUNL, and Notre Dame; re-accelerated radioactive ion beams at FRIB/ReA; upgraded in-flight and neutron-rich beam capabilities at ATLAS; and intensity upgrades at HIγS. To go with these facilities, new and upgraded detection systems have been developed that promise to increase sensitivity to very low reaction rates significantly. Examples include the SECAR recoil separator; novel active target approaches such as the MUSIC at ANL, ATHENA at Notre Dame, the optical TPC at HIγS, the AT-TPC at FRIB, ANASEN, TexAT; low-background

coincidence spectrometers at LENA; the St. George recoil spectrometer at Notre Dame; and advanced neutron detectors developed at Oak Ridge National Laboratory. Complementary to advanced direct measurements, progress in reaction theory has enabled the development of new indirect experimental techniques. These indirect approaches include the Trojan horse method and advances in the application of Asymptotic Normalization Coefficients and Spectroscopic Factors that have been shown to be able to provide cross section data at astrophysical energies. While free of the uncertainties from laboratory electron screening effects, the theoretical models used to extract the cross section introduce systematic uncertainties that need to be addressed and fully quantified with advances in reaction theory.

One of the major successes of the field were the advances in our precise understanding of the nuclear reactions in the Sun that led to major advances in the understanding of neutrino properties, including neutrino oscillations. Most recently, the Borexino neutrino detector observed neutrinos originating in the CNO cycle, providing a direct measurement of the solar metallicity [BOR20]. This constraint was only possible with well-measured CNO-cycle reaction rates, which are the result of many years of hard work with both above-ground and underground accelerators (see [ORE21] for a review). Additionally, experimental progress has been made in understanding the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ cross section at low energies [DEB17], and technological advances in experiment and nuclear reaction theory have led to new experimental cross section data for carbon burning reactions [ALI22]. On the other hand, advances in astrophysical observations often illuminate the limitations in our understanding. For example, recent observations have yielded high-resolution maps of ^{44}Ti in core-collapse supernova remnants [WEI20]. In order to use those observations to constrain the dynamics of the explosion, the reaction rates that influence ^{44}Ti yields must be well known. Recent work [SUB20] highlighted that our current understanding of the nuclear cross sections is poor, and identified influential reactions that should be the focus of experimental work. Several of these have already been constrained with experimental campaigns, and many more will be within reach of new rare isotope and stable beam facilities.

Origin of the heavy elements: Understanding the synthesis of the heavy elements, primarily those with atomic numbers greater than iron, remains one of the biggest open questions in nuclear astrophysics. Because fusion above iron is no longer energetically favorable, continued synthesis of the elements from iron through uranium must proceed principally through light particle capture reactions. It has been long known that at least two different broad classes of processes must contribute to producing heavy elements: the slow and rapid (*s*- and *r*-) neutron capture processes. Over the last decade, as fidelity has improved in nuclear data, astrophysical simulations, and the observational constraints, it has become clear that there are more than two components contributing [Sch22]. The weak and the main *s*-processes, a weak *r*-process (possibly driven primarily by charged particle reactions), likely multiple traditional *r*-processes, multiple intermediate neutron capture processes (*i*-process), at least two γ -processes for production of the rarest neutron-deficient stable isotopes, and the *vp* process are all competing to produce the heavy elements, providing both diverse environments and challenges in deconvolving the contributions that lead to the abundances we observe today. Together, these environments require a much broader, more complex, and more robust set of nuclear data, including lifetimes and masses, neutron-induced reaction rates on stable and unstable isotopes from stability to the neutron dripline, photo-disintegration reaction rates, alpha- and proton-induced reactions rates on heavy, unstable isotopes, fission probabilities and products, and information on nuclear isomers in both reactions and decays. While the proton-rich side of the nuclear chart has been somewhat accessible in the past, recent capabilities for production of intense neutron-rich beams, including FRIB as well as CARIBU at ATLAS, are opening new windows for investigation of these nuclear properties far from stability, which

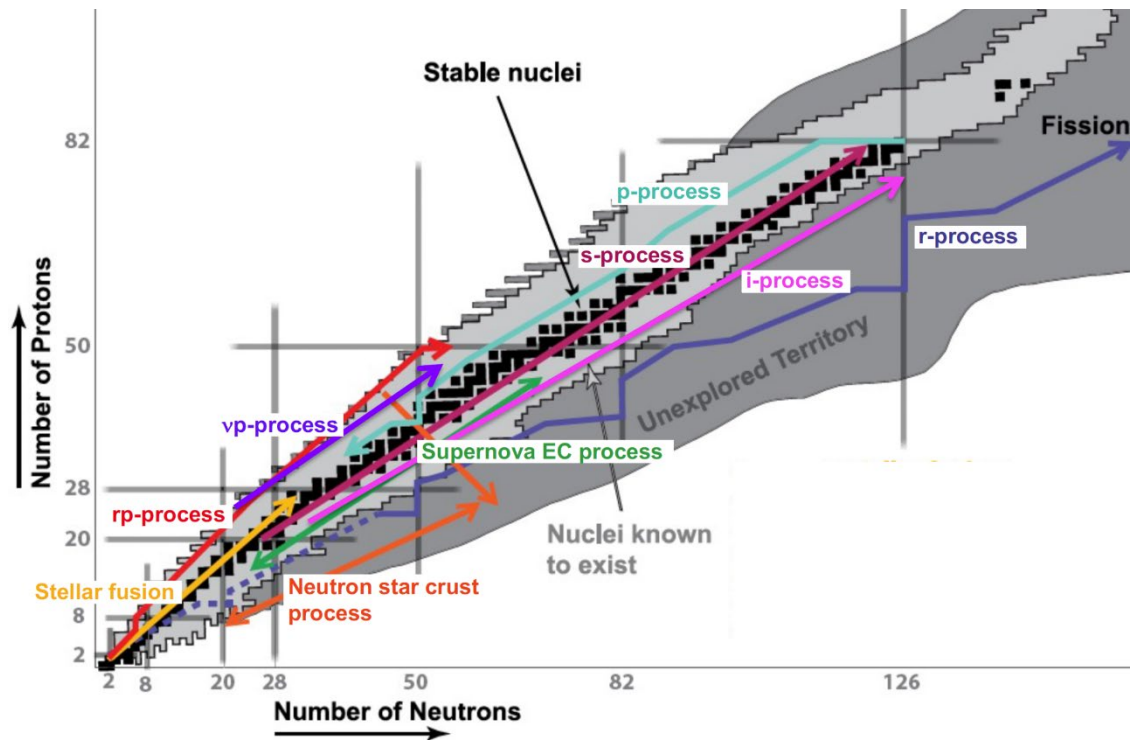


Figure 3.3: Schematic representation of the nuclear reaction processes in the cosmos. The number of processes that are thought to contribute to the origin of the elements has considerably increased in recent years, driven by new observations, new computer models, and progress in understanding of nuclear physics [Sch22].

will be critical for performing the measurements needed to answer the underlying questions of where and how these heaviest elements are made.

For the s-, r-, and i- neutron capture processes, the last decade has seen significant nuclear physics advances. Low-energy beams of the most neutron-rich isotopes have employed mass measurements with Penning traps, including the development of Phase-Imaging Ion Cyclotron Resonance (PI-ICR) measurements, reaching well into the r-process regime at exquisite resolution. An example are the recent rare-earth peak results from Argonne National Laboratory's CARIBU facility, which have, for the first time, been combined with machine learning techniques to begin constraining the conditions for the astrophysical site or sites of the r-process [Orf22]. Decay and beta-delayed neutron emission probabilities have been measured for neutron-rich isotopes of direct interest in the r-process at NSCL and more recently at a large scale in the BRIKEN campaign at RIKEN/RIBF [Hor19]. While the $^{13}\text{C}(\alpha, n)$ and $^{22}\text{Ne}(\alpha, n)$ reactions have long been known to be the primary neutron sources for the strong and weak s-processes, respectively, there were large uncertainties associated with these reaction rates. Recent experimental work, including direct and indirect measurements of these reactions, coupled with complex R-matrix analyses, has reduced these uncertainties, with further improvements in our understanding of these rates on the horizon [ALI22]. On the neutron capture side, significant advances in the brightness of time-of-flight neutron sources coupled to detector systems like those at LANSCE at Los Alamos have enabled refined measurements. Almost all of the cross-sections for stable isotopes for the weak s-process have been revisited and first measurements have been made on several of the radioactive s-process branch points. As important as developments in neutron beam and detector capabilities, isotope harvesting and production from NSCL at MSU and IPF at LANSCE have delivered short-lived samples for direct neutron measurements. For measurements far from stability at NSCL and ATLAS, major advances in indirect techniques to constrain Hauser-Feshbach neutron-capture cross sections for the i- and r-processes have been

achieved. In particular, theoretical nuclear reaction work to improve modeling of compound nuclear reactions has been essential to allowing the surrogate reaction method (SRM) to produce the first robust neutron capture rate predictions. Measurements of transfer reactions utilizing new, high-resolution, high-efficiency particle-gamma coincidence arrays such as GODDESS [Rat19] will continue to provide new cases for the SRM. In parallel, advances in the use of the Oslo Method, and the development of the b-Oslo and shape methods to reach nuclei farther from stability, have enabled the constraint of the nuclear level density and photon strength function, thus improving predictions of neutron capture rates on unstable nuclei without requiring direct measurements.

While much of the nucleosynthesis above iron is driven by neutron captures, a fraction of the heavy elements may also be synthesized by α -particle captures (weak r-process) under neutron-rich conditions, by a mixture of (n,p) and (p, γ) reactions in proton-rich environments (vp-process), or by photodisintegration (p-process or γ -process). Successful direct reaction-rate measurements have been performed for charged-particle reaction rates of importance to heavy element nucleosynthesis in all these scenarios. For example, the (α ,n) reactions on short-lived nuclides that synthesize heavy elements in the weak r-process are now being measured using a variety of complementary techniques such as the MUSIC detector at Argonne National Laboratory and FRIB, along with the HABANERO neutron counter and SECAR recoil separator at FRIB. Recently, work at LANSCE demonstrated that for sufficiently long-lived target nuclei such as ^{56}Ni , direct measurements of (n,p) reactions with neutron beams are possible for reactions of relevance for the vp-process. For more unstable nuclei, relevant (n,p) reactions can be also constrained by measuring the inverse (p,n) reaction. For instance, (p,n) reactions are being measured at energies of interest for vp-process nucleosynthesis using the SECAR recoil separator with neutron coincidences. Direct measurements of the inverse p-process reactions with total absorption spectrometers at the University of Notre Dame have constrained properties of p-process nuclei near $A = 100$.

NUCLEAR-DRIVEN TRANSIENTS: Considerable progress has been made in our understanding of thermonuclear explosions in stellar binary systems. X-ray bursts, associated with accretion from a binary companion onto the surface of a neutron star, are the most commonly observed astrophysical explosions in the Galaxy. These environments can synthesize proton-rich isotopes up to around $A \sim 100$ and produce observable, recurrent light curves, allowing a direct link between the astronomical observations and the underlying nuclear physics [Mei18]. Classical novae, explosive accreting binary systems involving white dwarf stars, can produce elements up to about $A=40$ (though the exact endpoint remains an open question), and a subset of systems may eventually lead to thermonuclear supernovae explosions. Recent experiments with radioactive isotope beams have identified rapid proton capture (rp-process) waiting-point nuclei and tied nuclear physics to the length of an X-ray burst through one-dimensional models of the so-called “textbook burster.” This has opened the door to using X-ray burst light curves of particular systems to extract neutron star properties provided accurate nuclear physics is available. Most of the masses and ground state half-lives of the nuclei involved in the rp-process are now experimentally known to a sufficient level of precision to not impact light curve models significantly [Mei18]; recent Penning trap mass measurements at NSCL and ANL around critical waiting points such as ^{56}Ni have solidified our understanding of the rp-process path. Thus, the largest remaining experimental challenges are in constraining the charged-particle reaction rates that impact the light curves and explosive nucleosynthesis. Direct measurements of these reactions are challenging experimentally, but considerable progress has been made in developing more intense radioactive isotope beams, more sensitive and higher-efficiency detectors and detection techniques, and additional indirect techniques to study these nuclei and constrain the reactions of interest. For example: developments of in-flight beams at ATLAS [RAISOR] have provided ^{30}P beams at better than 10^5 pps; a recent proliferation of windowless gas targets and active targets such as JENSA, ANASEN, MUSIC, and the AT-TPC, among others, have allowed for direct studies of the (α ,p) and (p, α) reactions that drive the breakout from the lower masses into the rp-process

approaching the astrophysically-relevant energy regimes, while SECAR at FRIB will provide the world-unique coupling of a recoil separator for astrophysical capture reactions with a fragmentation beam facility; and increases in sensitivity and resolution from devices like GRETINA, GODDESS, HELIOS and SOLARIS, FDSi, and recently-refurbished split-pole spectrographs at several ARUNA laboratories have provided unprecedented precision for studies of the nuclear levels critical for our understanding of explosive nucleosynthesis.

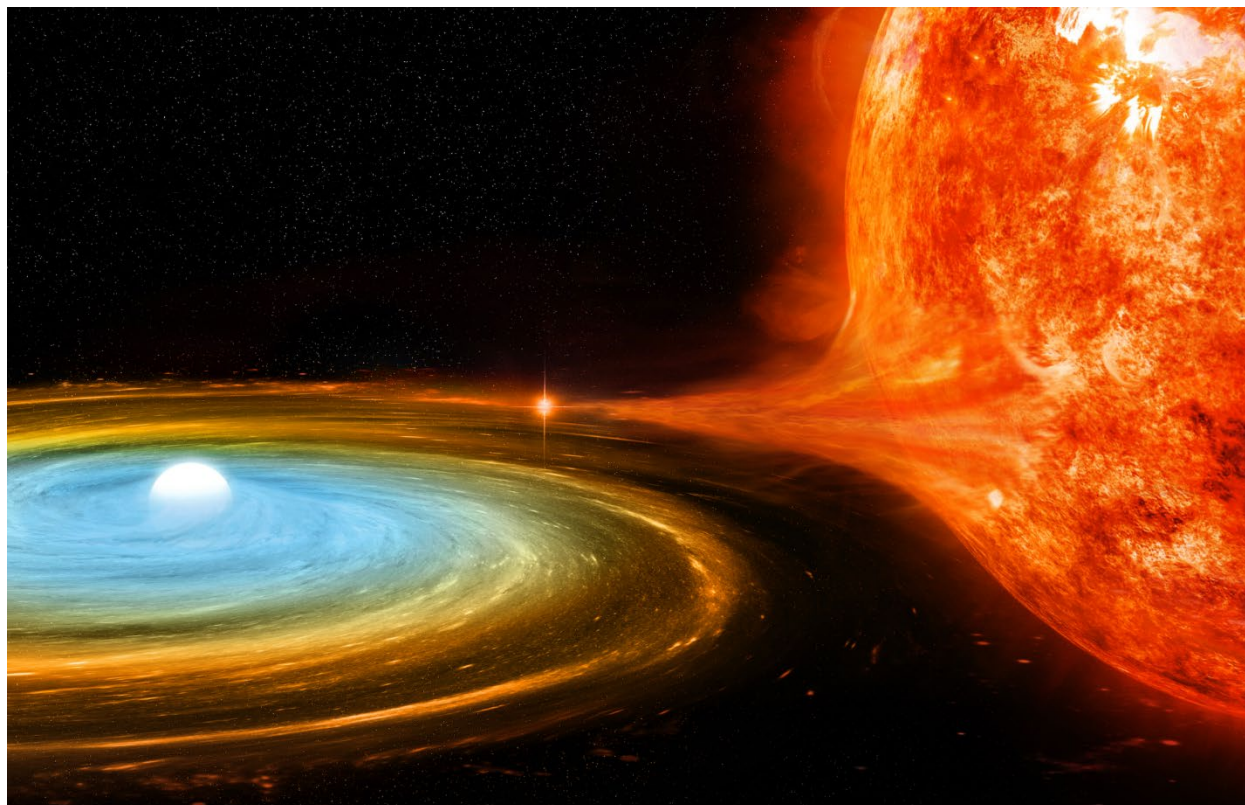


Figure 3.4: Artist conception of an accreting neutron star system. Rare isotope physics governs thermonuclear explosions on the surface of the neutron star (object on the left) observable as X-ray bursts as well as heating and cooling of the neutron star interior. With advances in nuclear physics these systems offer the unique opportunity to probe the response of neutron stars to mass increases. Image credit: NASA/CXC/M.Weiss.

Core collapse supernovae, thermonuclear supernovae, and kilonovae are nuclear transients that are the prime targets for multi-messenger astronomy. Interpreting their light curves across messengers requires experimental understanding of the underlying nuclear physics. Electron capture and beta decays involving ground and highly excited nuclear states are key to interpreting the early neutrino signal from core collapse supernovae, especially in preparation for a future galactic supernova event. Charge-exchange-reaction measurements with stable nuclei have now provided extensive constraints on weak interaction strengths that have guided the development of much more reliable theoretical shell-model predictions and, most importantly, have enabled quantification of nuclear uncertainties [Lan21]. Together with advances in the understanding of the carbon fusion reaction (noted in **Stars**, above), these charge-exchange reactions have also led to better understanding of nucleosynthesis in thermonuclear supernovae. Kilonovae are powered by the radioactive decay of r-process nuclei ejected in neutron star mergers. The experimental advances in understanding the r-process discussed above have therefore a direct impact on interpreting kilonova observations such as the recent observation of the kilonova associated with the gravitational wave detection event GW170817 [Hor19].

A different type of nuclear-powered transient in the X-ray sky are transiently accreting neutron stars with particularly long periods where accretion turns off and the cooling of the neutron star crust, heated during the accretion phase by nuclear reactions, can be observed over timescales of years [Mei18]. These systems have now become unique probes of both dense matter physics below nuclear density in neutron star crusts (such as neutron superfluidity, nuclear pasta, and unique types of nuclear reactions), as well as higher density phenomena in the neutron star core. Experiments have begun to address some of the important nuclear physics of neutron-rich nuclei from stability to beyond the neutron dripline up to mass $A \sim 100$. Nuclear masses directly affect nuclear heating and cooling via Urca processes, and measurements have been extended to relevant neutron-rich nuclei using time-of-flight and Penning trap techniques. Measurements of beta-delayed gamma rays and neutrons have provided constraints on ground state to ground state transition strengths, a key pathway for nuclear transformations in accreted crusts. Density induced heavy-ion fusion reactions are important heat sources, and first experiments have begun to explore how such reactions depend on and may be modified by neutron richness. Yet, none of these types of measurements have reached the neutron dripline over the relevant mass range, and the unknown physics of these extremely neutron-rich nuclei remains a limitation that needs to be addressed in the future.

DENSE MATTER: The equation of state of *dense* matter — in the range of atomic nuclei and neutron stars — describes the relation between pressure, density, temperature, energy, and composition; for example, when nuclear matter is compressed, it heats up, and the amount of heating depends on the composition. The equation of state influences neutron star properties and features of neutron star mergers, and thus impacts sites of neutron-capture nucleosynthesis [Sch22]. The equation of state below normal nuclear density impacts surface features of neutron stars, and above normal nuclear density, the properties of the core. In some sense, a neutron star is an atomic nucleus but with a radius about one quintillion times larger: the same nuclear physics is at work in nuclei and in neutron stars (with the addition of gravity in the neutron star), and this allows us to test our models of nature at its extremes; the nuclear equation of state connects nuclei to the cosmos.

The nuclear equation of state is constrained by terrestrial measurements of nuclear collisions and by astronomical observations. Currently, the most impactful aspect to pin down is the symmetry energy, which describes how the equation of state depends on an excess of neutrons over protons. Heavy-ion collision experiments using the SpiRIT time projection chamber at RIKEN/RIBF compared the yields of measured pions to predictions of microscopic transport models to deduce a constraint on the symmetry energy significantly above normal nuclear density. The PREX collaboration at Jefferson Laboratory has also provided new constraints on the equation of state near saturation density using parity violating electron scattering to measure the thickness of the neutron skin on ^{208}Pb . Many measurements of heavy ion reactions (including at MSU with the LASSA and HiRA arrays, and at Texas A&M with the NIMROD array) have examined particle yields and particle flows to place constraints below saturation density; the clustering of nucleons is observed to modify the equation of state at very low density. Measurements of nuclear masses, nuclear dipole polarizability, and isobaric analog states place significant constraints near normal nuclear density and below. See [LYN22] for recent experimental summary and [BUR21, COL20, MCI19, BAI19, ROC18] for recent reviews; see [WOL22] for recent review of progress in theoretical development. These measurements are taken in context with the measured neutron star mass-radius relation by NICER, and gravitational wave signatures measured with LIGO, to provide a coherent description of atomic nuclei and cosmological objects [LYN22]. Indeed, we have just seen the dawn of a new era with the measured rippling of spacetime by LIGO and the interiors of neutron stars by NICER, allowing new sensitivity to the details of the strong nuclear force.

CROSS CUTTING TOPICS: Deep connections between nuclear physics and astrophysics are critical for nuclear astrophysics. This is especially true for experimental nuclear astrophysics. The motivation for experiments comes

directly from observations and modeling of astrophysical phenomena, and the results must be implemented in astrophysical models and included in the interpretation of observations to make progress. The Joint Institute for Nuclear Astrophysics (JINA), and JINA-CEE in the US, as well as similar centers in other countries inspired by the success of JINA, were instrumental in creating these critical connections and forming an interdisciplinary nuclear astrophysics community in the US and internationally. The exchange of experimental nuclear data across field boundaries is a particularly important aspect. This requires the conversion of experimental results into astrophysically-usable data by combining a broad range of experimental and theoretical information in reaction theoretical frameworks such as R-Matrix Theory, as well as corrections accounting for the astrophysical environments. A number of public databases are now maintained by several institutions [e.g., Cyb10, SAL13]. Nevertheless, there remains a significant lag between new measurements and implementation of results that needs to be addressed in the future. In the last decade, pioneering efforts have begun to systematically implement rigorous statistical analysis and meaningful uncertainties [IL15]. Modern reaction networks are beginning to include these uncertainties [SAL13], though incorporating theoretical uncertainties with proper correlations remains a challenge. These tools have opened the pathway to quantifiable comparisons between models and observations that are of particular importance in the era of multi-messenger, precision astrophysics.

MAJOR OPPORTUNITIES

With historically unique joint progress in experimental, theoretical, computational, and observational capabilities, there will be unprecedented opportunities to address long standing grand challenges in nuclear astrophysics. In the coming decade, FRIB, complemented by the ANL nuCARIBU and N=126 Factory upgrades, will provide unprecedented experimental access to rare isotopes along astrophysical reaction chains. Upgraded stable, neutron, and gamma beam facilities, together with novel detection and separator techniques will probe stellar reaction rates in new energy regimes and with new precision. These experimental advances will provide guidance to and be complemented by unprecedented nuclear theory predictions driven by large-scale computing and novel machine learning techniques. Computer models of nuclear astrophysics sites will reach unprecedented fidelity in three dimensions to connect nuclear physics with astronomical observables.

And the wealth of these astronomical observations is also poised to explode in the coming decade. With refinements in sensitivity, LIGO is expected to detect increasing numbers of compact object mergers, leading to a treasure trove of data for dense matter studies. New neutrino detectors (Hyper-Kamiokande and possibly DUNE) will be deployed that can detect neutrinos from core-collapse supernovae throughout the Local Group of galaxies. Analysis of stardust and the ever-growing stellar spectroscopy data sets will provide a detailed map of the history of chemical evolution of our Galaxy. A large number of new electromagnetic observational facilities have either recently entered service, or are being developed for deployment in the next few years, that will allow us to better probe nuclear physics properties of astrophysical phenomena. Key new missions include the James Webb Space Telescope (JWST) infrared mission, the UV Ultraviolet mission (to be launched in 2025), and the UVEX mission (currently in phase A approval at NASA). For neutron star mergers, these will be among a wide range of ground- and space-based facilities prepared to follow up gravitational-wave detections and provide broadband coverage of the kilonova to constrain the uncertainties in tying the observed emission directly to detailed r-process yields. Infrared observations, coupled with optical and ultraviolet, can determine the extent of high-opacity material in the ejecta (e.g., lanthanides) and will provide increasingly accurate r-process ejecta masses. The potential to detect line features (both single and merged features) may even provide yields for specific r-process elements. Ground-based, wide-field optical surveys are currently discovering multiple transients every day, many of which are followed up with panchromatic photometry and spectroscopy. Future surveys, such as the Vera Rubin Telescope, are expected to discover millions

of nuclear-powered transients in the coming decade. The Compton Spectrometer and Imager (COSI) mission (to be launched in 2027) will observe gamma-rays from the decay of radioactive elements in neutron star merger remnants (direct detection of r-process production), supernovae and supernova remnants. These gamma-ray observations provide the most direct observations of the production of a set of interesting isotopes.

This myriad of new developments, both from within the nuclear physics community and from supporting communities, will open up major scientific opportunities in nuclear astrophysics for the coming decade:

UNRAVEL THE ORIGIN OF HEAVY ELEMENTS: With progress in the previous decade pointing to a surprising diversity in the heavy element nucleosynthesis processes, we are now in a position to begin to identify the various relevant astrophysical sites, their nuclear reaction sequences, and their relative contribution over the history of the Galaxy. This will be enabled by combining an extraordinary broad range of nuclear physics (from stable nuclei to the most exotic rare isotopes), observations, stardust analysis, and astrophysical models of stars, supernovae, neutron star mergers (see below), and the chemical evolution of galaxies.

DETERMINE THE NUCLEOSYNTHESIS CONTRIBUTIONS OF NEUTRON STAR MERGERS: Neutron star mergers were long suspected to be a major contributor to heavy element nucleosynthesis. There is now an opportunity to combine gravitational wave triggered kilonova observations with new rare isotope physics from experiment and theory, new equation of state physics (see below), new neutrino physics, high fidelity end-to-end computer models, and stellar spectroscopy data to quantify this contribution for the first time. This will also make nucleosynthesis observables a window into the dense matter and neutrino physics deep inside compact object mergers.

ADVANCE THE FUNDAMENTAL UNDERSTANDING OF LOW ENERGY NUCLEAR REACTIONS AND NUCLEOSYNTHESIS OF STARS: With novel experimental approaches – direct and indirect -- in concert with advances in reaction theory, there is now an opportunity for a new understanding of the extremely low energy nuclear reactions that drive stars. Together with advanced three-dimensional simulations of stellar interiors and core collapse supernovae, and novel observational windows into stars, such as asteroseismology, neutrino signals, stardust, and compact remnant distributions sampled by gravitational wave observations, there is a prime opportunity to arrive at a new understanding of the nuclear physics of stars, and the elements they create.

MAP AND UNDERSTAND THE NUCLEAR-POWERED TRANSIENT SKY IN UNPRECEDENTED DETAIL: Surveys like that planned with the Vera Rubin Telescope will reveal time dependent astrophysical scenarios in prodigious numbers due to their unprecedented sky and time coverage. Many of these time-variable phenomena are nuclear physics driven. In the coming decade, we will be able to understand the electromagnetic, nucleosynthetic, radioactive, and stardust fingerprints of a broad range of transients such as novae, supernovae, X-ray bursts, kilonovae, cooling neutron stars, as well as potentially novel, hitherto undiscovered, types of transients. This understanding will be enabled by a combination of novel instrumentation and facilities to measure nuclear reactions on stable and unstable nuclei and significantly advanced computational models of astrophysical sites.

A GOLDEN ERA OF NEUTRON STARS: The coming decade can be expected to be a golden era of neutron stars. Gravitational wave observations of neutron star mergers with future LIGO runs, as well as next generation gravitational wave detectors, will expand this new window into neutron stars and put neutron star physics at the forefront of science. Breakthroughs can also be expected in neutron star mass and radius measurements, heavy ion collision experiments, and in nuclear theory of dense matter inside neutron stars. There is an opportunity for unprecedented understanding of neutron stars, and their central role in nucleosynthesis and nuclear-driven transients. At the same time, understanding neutron stars will lead to a new fundamental understanding of nuclear matter, and the extreme densities will enable us to probe neutrino and dark matter physics in new ways.

3.1.2 THEORETICAL NUCLEAR ASTROPHYSICS OPPORTUNITIES

STELLAR EVOLUTION INCLUDING SOLAR MODEL: With new observational windows into stars opening up, and major improvements in understanding the slow nuclear reactions in stars on the horizon, there is now a major opportunity for theory to advance stellar models by combining advanced 3D and 3D informed 1D simulations for critical phases with high resolution 1D simulations along the entire stellar evolution sequence and better account for crucial effects such as mixing, rotation, magnetic fields, and mass loss. This will link nuclear processes in stars with new nucleosynthetic signatures of elements up to bismuth in large scale stellar spectroscopy datasets, stardust; with astroseismology data that reveal the interior composition of stars and can directly probe convective mixing processes; and in connection with advanced core collapse supernova models with black hole and neutron star mass distributions probed by gravitational waves. Machine learning approaches can play an important role in comparing results from large scale stellar model grids with large observational data sets across messengers. Advanced stellar models will be of particular importance for nuclear astrophysics to reveal and fully characterize novel nucleosynthesis processes that emerge in 3D simulations such as the intermediate neutron capture process. A particular opportunity are advanced models of first stars to reveal their unique nuclear processes in light of JWST pushing direct observations into this epoch and stellar spectroscopy surveys finding new signatures in the oldest stars. Advanced stellar models will also be critical for providing reliable progenitor models for core collapse supernova simulations, thus forming the basis for reliable predictions of explosive nucleosynthesis and compact object formation.

CORE-COLLAPSE SUPERNOVAE: The success of CCSN simulations in the past decade lays the groundwork to pursue quantitative agreement with a wider range of observations. From this wider variety of observational constraints, we hope to better understand the stellar properties that impact the explosion, with a goal of mapping observed explosions back to their stellar progenitors. Matching a wider range of observations, many of which depend on the nuclear composition of the ejecta, will require more detailed treatment of the nuclear composition in the ejecta. It will also require higher fidelity in all of the factors that determine the neutronization, since this determines much of the nuclear composition. As a result, these models will only be as good as our understanding of the nuclear equation of state and neutrino-matter interactions. They will also require a better understanding of the role that neutrino oscillations play in CCSN, as well as a means to include this important physics in a cost-effective manner within multi-dimensional simulations. Finally, matching the wider range of observations will require “end-to-end” CCSN simulations, encompassing the late stages of massive stellar evolution, through core collapse, the revival of the supernova shock, the completion of the nucleosynthesis and the revelation of these newly formed isotopes to the Universe. Only with high fidelity, end-to-end simulations can we truly use astronomical observations to teach about the origin of the elements in supernovae.

NEUTRON STAR MERGERS: Despite the amazing progress of the past decade, the question remains, Are neutron star mergers the primary site of production of r-process elements? With astrophysical and nuclear physics uncertainties expected to shrink significantly in the next few years, an answer to this question appears to be within reach. However, solving the r-process problem will require the development of a new generation of theoretical models with more sophisticated neutrino transport and general-relativistic magnetohydrodynamics to correctly capture the neutronization of the ejecta. “End-to-end” simulations, in the NSM case connecting the last tens of millisecond of the inspiral and merger dynamics, which can be probed with gravitational wave observations, to the light curve and nebular spectra of the emerging kilonova, which we will be able to observe with JWST, will be critical. Such models will allow us to quantify the nucleosynthesis yields of mergers using upcoming multi-messenger observations. To aid in sorting out the origin of the r-process, alternative possible sites of the r-process, such as

electron-capture supernovae, magnetorotational supernovae, and collapsars should also be investigated. Here the simulation technology developed for mergers and core-collapse supernovae will also be important.

End-to-end models of mergers will allow us to constrain the equation of state of neutron stars using the full information available. This includes the gravitational wave signal, which encodes the tidal deformability of neutron stars, and the kilonova, which depends sensitively on the lifetime of the remnant. As gravitational-wave detectors increase their sensitivity, improved waveform models will need to be developed using high-precision numerical relativity data. Non-thermal photons and neutrinos produced in mergers could provide additional constraints on the nature of dense matter, once next-generation simulations reliably determine the mechanism by which relativistic outflows are launched in mergers. The post-merger of neutron star binaries could reveal the presence of phase transitions in dense matter, which could be detected with next-generation gravitational-wave experiments, such as Cosmic Explorer. While these experiments are not expected to operate in the next decade, theoretical models are urgently needed to guide design decisions for these instruments.

R-PROCESS: Modeling r-process observables requires a diversity of improved nuclear data, including neutron capture rates, neutron separation energies, nuclear masses, decay branching ratios, alpha decay rates, beta-decay properties (half-lives, Q-values, neutron emission probabilities, and gamma spectra), as well as fission properties (barrier heights, fission yields, neutron multiplicities, gamma spectra, and rates for all fission channels). Currently, for neutron capture, there exist direct measurements on stable nuclei and indirect measurements within a few neutrons of stability, but experimental and theoretical approaches are being pioneered to move more reliably into the neutron-rich regions. Beta-decay studies are of importance to abundance predictions as well as multi-messenger observables, with beta-decay heating impacting light curves and MeV beta-gamma spectra being crucial to interpret electromagnetic signals from events and remnants. With FRIB being able to produce hundreds of neutron-rich lanthanide isotopes for the first time, the question of whether local enhanced stability produces the so-called r-process rare-earth peak at $A \sim 164$ can be definitively addressed. Particularly with the FRIB400 upgrade and the ATLAS N=126 Factory, the ability to reach nuclei closer to the predicted r-process path in neutron star mergers could be unlocked. The N=82 shell closure could be mapped out all the way to the dripline, solidifying the local nuclear physics properties shaping the second peak abundances. There are especially opportunities to make big leaps in our understanding of the N=126 shell closure, where there presently exists almost no experimental information on the neutron-rich side of stability. N=126 structure not only crucially determines the abundance of elements like gold and platinum, but also directly influences how strongly actinides are populated since the synthesis must overcome this final gateway before proceeding into the actinides.

The importance of understanding neutron-rich actinide species has become increasingly pressing in the last few years. Fission can impact kilonova light curves and MeV gamma rays, as well as the final r-process abundances via fission cycling. Fission properties in the neutron-rich regions are also connected to some fundamental questions about the r-process. Two important examples are: (1) whether or not the so-called superheavy elements ($Z > 103$) can be produced in astrophysical environments, which depends on unknown fission rates and (2) do r-process enhanced, metal-poor stars (believed to capture the products of one to few r-process events) show some element abundances to truly be “universal” from star-to-star, which could be connected to fission cycling. Currently, the fission rates and yields available in the neutron-rich regions are almost purely theoretical, with key species like ^{254}Cf lying just within the border of experimentally explored nuclei. Therefore, with key unknowns presently lying in exotic, largely unprobed regions near N=126 and the actinides, there is significant opportunity for nuclear physics progress over the next few years to constrain the modeling of r-process events.

WHITE DWARF TRANSIENTS: Current and upcoming observational surveys are expected to expand the early- and late-time observations of Type Ia SNe in both the optical and the IR. They could also reveal rarer types of nuclear-powered transients that are, as of yet, unobserved, representing a new frontier for white dwarf transient astrophysics. Higher fidelity, multidimensional hydrodynamical simulations of SNe Ia, including more extensive nuclear networks spanning in excess of 50 isotopes, followed by non-LTE radiative transfer synthetic spectra and light curves, spanning days to even years after the explosion, are needed to compare the hydrodynamical models against the coming wealth of observations. A new generation of classical novae simulations are also needed to confront the coming observations, encompassing the multidimensional and multiscale nature of the underlying problem. For example, multidimensional simulations of the explosion and its interaction with the binary companion are essential to understand ejecta from the nova outburst and the restarting of the accretion process.

NEUTRON STAR TRANSIENTS: With new computing resources coming on line, we will be able to model larger regions of the neutron star surface in full three-dimensions with moderate-sized reaction networks to be able to understand rp-process nucleosynthesis and the physics of the flame propagation. Fully resolved, full-star simulations will remain out of reach, but new subgrid models or true multiscale models can be developed from the current and near-future work to allow us to bootstrap up to the full star. Lightcurve modeling of these multidimensional simulations will then be required to connect to the observations and help us understand the nuclear equation of state.

NEUTRINO OSCILLATIONS: Observations of core-collapse supernovae and neutron star mergers via multiple messengers will probe the behavior of neutrinos in extreme neutrino densities. While the previous decade witnessed a rapid growth of putative neutrino flavor-changing phenomena, the next decade could bring confirmation of these processes by the combination of simulation and observations. Including realistic flavor-changing effects in end-to-end simulations of supernovae and mergers is now theoretically possible, though technically very challenging. In addition to removing a significant uncertainty affecting the mass ejection and nucleosynthesis occurring in CCSN and NSM models, this will offer the opportunity to probe fundamental physics and chaotic quantum kinetics to explore possibilities of additional undiscovered neutrino flavors, undetected neutrino interaction channels, and the currently unknown fundamental symmetries of neutrinos.

PHYSICS OF NEUTRON STARS: If a sufficient number of double neutron star mergers are captured by Advanced LIGO or Cosmic Explorer, gravitational wave observations of double neutron star mergers (when combined with chiral effective field theory) promise to determine the relationship between pressure and energy density in dense matter with unprecedented accuracy. Over the next 10 years, novel combinations of gravitational wave and electromagnetic observations of neutron stars, experiments on nuclei, and advances in nuclear theory will go further. We will begin to constrain the nature of the strongly-interacting degrees of freedom in neutron star interiors and the role that these degrees of freedom play in determining processes like X-ray bursts, magnetar flares, X-ray and radio pulsations, and others. The high temperatures potentially reached in neutron star mergers motivate a deeper connection between the low-energy nuclear theory community and the heavy-ion theory community, which works at high densities and high temperatures.

NUCLEAR THEORY FOR ASTRO: Nuclear structure and reaction theory will remain critical for progress in nuclear astrophysics simulations. Theory will be needed to plan and interpret laboratory experiments, for evaluating nuclear structure and reaction data, and for predicting nuclear properties that cannot be measured, but are needed for simulations.

Current research is primed to provide nuclear structure and reaction predictions based on microscopic approaches or, where necessary, on carefully calibrated phenomenological models — across the chart of the nuclides. Nuclear structure descriptions based on shell-model approaches and density functional theory (DFT) complement each other and are expected to see continued improvements in applicability (reach) and accuracy. Both types of approaches will require new and improved interactions, extensions to accommodate the underlying formalisms more fully, and high-performance computational resources to perform large-scale calculations. Calculations for chains of isotopes, along with comparisons to suitable experimental data and quantification of uncertainties, will provide confidence when extrapolations to isotopes far from stability are needed. Predictions of masses, Q values, gamma-ray strength functions, level densities, beta-decay rates, and fission properties will benefit from these improvements.

Next-generation reaction theory needs to integrate state-of-the-art structure theory with modern reaction frameworks, for both direct and statistical reactions. *Ab initio* reaction descriptions that are based on the Resonating Group Method (RGM) already treat both aspects on equal footing — for light nuclei. RGM-based models can be used to explore and account for deformation, clustering, and continuum effects. Reactions with complex particles need to be explored more fully. Extensions to medium-mass nuclei will be enabled through the use of symmetry-adapted shell-model bases.

The microscopic interactions necessary for structure and direct reaction calculations are also critical ingredients for dynamical transport models. These models are important in confronting heavy ion collision data in order to constrain the equation of dense matter relevant to neutron stars. Systematic comparisons of transport model calculations will improve systematic uncertainties.

Direct-reaction calculations involving medium-mass and heavy nuclei are also poised for significant upgrades. Most importantly, simple nuclear structure models used in reaction calculations can now be replaced by state-of-the-art structure theory. This will also enable better planning and interpretation of laboratory experiments.

Statistical (Hauser-Feshbach, HF) reaction theory requires significant nuclear structure input. The trend to replace phenomenological structure models (for level densities, gamma strength function, etc.) by microscopic calculations will result in increased predictive power. Since HF reaction descriptions make an averaging assumption, which is not valid in all regions relevant to astrophysics, the limits of its validity need to be established. Rigorous methods that correct or replace the HF approach for regions of low level density and approaches that provide a bridge between the HF regime and R-matrix descriptions for isolated resonances are needed, particularly where no experimental data is available.

With further theory development, we can make indirect reaction approaches, e.g., the Trojan Horse and Surrogate Reactions methods, more broadly applicable, to cover additional desired reactions and a larger number of isotopes. Developing robust descriptions of beta decay and beta-delayed neutron and gamma emission processes will provide important information for nucleosynthesis simulations.

The impact of the astrophysical environments on the nuclei of interest is a challenge that can now be tackled. Finite temperatures lead to the population of excited nuclear states and require that reactions on such states be studied. Plasma screening effects can be revisited, using improved nuclear reaction theory. Opportunities exist for nuclear theorists and astrophysics modelers to investigate how to better match the structure and reaction properties to the quantities used in the actual simulations.

The increased focus on uncertainty quantification for nuclear theory predictions is expected to persist. Challenges in providing meaningful uncertainties that can be propagated through to astrophysics simulations remain. At the

same time, uncertainty quantification is critically important for assessing the impact of potential experimental efforts and for interpreting astrophysical observables.

More broadly, advances in nuclear structure and reaction theory, such as those outlined in Sec. 1 (Nuclear Structure and Reactions Theory), will result in better predictive power and therefore provide benefits to nuclear astrophysics simulations. In turn, connecting nuclear properties to astrophysical observations, will provide additional observables that reflect those nuclear properties and test our understanding of all ingredients of nuclear astrophysics.

COMPUTATIONAL OPPORTUNITIES: The increasing capabilities of leadership computing platforms in the coming years will be needed to enable many of the advances in simulations described above, along with continued support in bringing nuclear astrophysics simulation codes to the evolving architectures. Similar advances in the computing platforms and codes are needed to enable improvements in the nuclear structure and reaction calculations upon which the simulations rely. Large-scale shell-model and DFT-based structure calculations, as well as some nuclear-reaction calculations and fission predictions will push computational capabilities, especially if calculations are to be performed for the large number of isotopes whose properties are needed for astrophysics simulations.

We also see tremendous opportunity in the coming decade to take advantage of Machine Learning (ML) in a variety of ways in nuclear astrophysics. We have already, for example, seen success building sub-grid models for the turbulent cascade below the resolution of current models based on ML analysis of small scale, high resolution hydrodynamic simulations, and other similar investigations are planned for other sub-grid physics. ML methods have been explored to calculate nuclear masses; other investigations into systematic nuclear properties and the use of emulators to allow for uncertainty quantification have been initiated. Initial work has also recently been done on modeling nuclear reaction networks with a neural network to replace the expensive integration. This can be particularly useful for initial iterations in high-order integration methods for coupling reactions and hydrodynamics. One particular area of interest is to build emulators for expensive high-performance computing simulations, for example, for use in matching observed events to progenitor systems. However, even as our use of ML increases, the need for high-performance computing simulations will remain, and even increase, to serve as training sets of increasing fidelity for the emulator development.

3.1.3 EXPERIMENTAL NUCLEAR ASTROPHYSICS OPPORTUNITIES

STARS: With recent investments in nuclear facilities and devices, we are well positioned to seize on opportunities to address long-standing fundamental open questions about stellar reaction rates at very low energies to better understand the stars. This will open up opportunities to address new and long-standing open questions concerning solar neutrino emission, the origin of the elements up to the iron region, changes in nucleosynthesis pathways in new dynamic multi-D simulations of stellar interiors, neutron star and black hole mass distributions, and the nature of the nucleosynthesis pathways in the first stars formed after the Big Bang, whose signatures can be observed in the oldest stars. An improved nuclear theory supported pipeline for experimental results, forging the connection from cross sections, to nuclear data, to stellar modeling input will facilitate new discoveries, and is essential for a thriving nuclear astrophysics program.

The cross sections of the reactions needed to understand dynamic stellar burning are small and span stable and radioactive nuclei. To make headway in their measurements, we must take a multi-pronged approach using a wide variety of techniques [ALI22, Sch22]. Low-energy cross section measurements, when possible, should be pursued both above ground and below ground. Advances in accelerator and detector technology make some above-ground measurements competitive, but a sophisticated underground laboratory would establish the United States' leadership in the field. Novel approaches using high temperature and high-density plasmas, e.g., at NIF, will offer

opportunities to probe astrophysical reactions in a plasma environment and to take advantage of high projectile densities, for example to study multi-neutron capture sequences [Bur22].

For reactions involving radioactive species, recently developed active-target detectors, recoil separators, and gas targets will be a key resource. An intense reaccelerated radioactive ion beam program at FRIB and in-flight beam program at ATLAS will be necessary to resolve uncertainties in explosive environments, for example, the synthesis of observable gamma-ray emitters in core collapse supernovae such as ^{44}Ti , ^{56}Ni , and many more. This is particularly timely and exciting in light of the future COSI gamma-ray mission. For long-lived radioisotopes, the capability to produce intense, high-quality beams from harvested material will enable rapid progression in our understanding of near-stability nucleosynthesis.

In many cases, direct cross section measurements are not possible. Novel indirect techniques will be an essential complementary tool in constraining reaction rates in stars [Tri14, Sch22]. Time-reversed reaction cross section measurements with time-projection chambers are becoming powerful tools (e.g., at HIγS), and particle-transfer reactions and beta-delayed particle decay measurements have proven to be powerful tools for extracting critical nuclear structure information. The Trojan Horse Method also offers new opportunities to obtain cross section information using indirect reactions [Spi19]. Advances in nuclear theory will be essential to quantify and reduce systematic errors.

ORIGIN OF THE HEAVY ELEMENTS: With the FRIB facility, the proposed FRIB400 upgrades, and the upcoming N=126 Factory and nuCARIBU upgrades at ANL, there is now a tremendous opportunity to address the wide range of nuclear physics inputs needed to understand the new diversity of astrophysical environments that appear to contribute to the heavy-element nucleosynthesis puzzle [Sch22]. A particular exciting prospect is for experiments being able to reach many of the extremely neutron-rich nuclei critical for the r-process and to answer some long-standing questions concerning the element distributions produced in various r-process sites, including the synthesis of superheavy elements and isotopes and their possible signatures [Hor19]. As masses and decay rates are critical, coupling decay spectroscopy using a full scale FDS [FDS] and mass measurement capabilities, like PI-ICR, is essential to delivering the greatest impact from these rare isotope beam advances. Time-of-Flight mass measurements, while of lower precision than the Penning Trap measurements, will allow the greatest reach, to potentially understand the neutron dripline and map trends in nuclear masses from evolving nuclear structure. This will be essential for r-process nucleosynthesis predictions from NS-merger environments [Hor19] as well as neutron star crust models (see below). Further, these beam production methods will open, in many ways for the first time, systematic studies of the roles nuclear structure effects far from stability, such as shell and sub-shell closures, shape changes, and isomeric states, play in the nuclear burning and the decays that together create the observed elemental and isotopic abundances.

Past investments have brought neutron-induced nucleosynthesis into a new era where direct and indirect techniques can together offer substantially improved, experimentally constrained reaction rates for unstable, neutron-rich isotopes in wide regions, which previously were completely reliant on Hauser-Feshbach theory. For the Surrogate Reaction method, the FRIB400 and ReA12 upgrades at FRIB as well as the development of the ISLA [ISLA] separator will be key to full utilization. While b-Oslo methods already have reach due to the low beam rates required, advances such as the FDS [FDS], N=126 Factory and nuCARIBU at ATLAS, and FRIB400 will both extend the range of isotopes that can be produced as well as provide decay information even in regimes of beta-delayed neutron emission, where current total absorption techniques are challenged. Critically, as these nascent methodologies become more mature, we can investigate through reaction modeling advances where the different approaches have the most impact. On the direct measurement frontier, advances in neutron beam intensities at

LANSCCE at Los Alamos and SARAF in Israel enable a new generation of direct neutron capture measurements on long-lived targets near stability, particularly on unstable isotopes, in regimes of astrophysical interest. Recent demonstration of rare-isotope production, harvesting and target fabrication for follow-on direct measurement by both FRIB and LANSCCE have delivered on a long-standing promise. Direct measurements on isotopes with lifetimes as short as 10 days are now within our grasp. This opens an opportunity to extend precision neutron capture rate measurements in the s-process to the branch point isotopes that are critical to constrain astrophysical conditions and stellar mixing processes. Finally, and most ambitiously, demonstration of (p, γ) reaction measurements in a rare-isotope ring at GSI have spawned the concept of using a storage ring with a neutron target to make possible direct measurement of neutron-induced reactions on isotopes with lifetimes as small as seconds a possibility, which would revolutionize our understanding of nucleosynthesis in the most neutron-rich nuclei. Both TRIUMF and LANSCCE are pursuing first steps to enable this needed next generation advance, which will truly open a new horizon for nuclear astrophysics.

Ongoing and future advances to rare isotope beam facilities that push isotope production to more intense beams near stability will offer opportunities to measure most of the charged-particle reactions of the weak r-, νp -, and p-processes. This includes FRIB and the FRIB400 upgrade, and the nuCARIBU facility at ANL. Instruments such as SECAR, HABANERO, and MUSIC are key resources for direct measurements of (α ,n) reactions relevant for the weak r-process.

Quasi-monoenergetic gamma beam facilities such as H γ S provide a unique opportunity to study the gamma-induced proton, neutron, and alpha emission on p-process nuclei. Precise measurements of these (γ ,p), (γ ,n), and (γ , α) reaction cross sections at multiple incident gamma energies will provide a stringent and model-independent constraint on the optical model potentials used in statistical model calculations of p-process reaction rates. Improving the techniques for this direct measurement effort utilizing gamma beams, including the use of silicon detectors, time-projection chambers, and n- γ discriminating materials, will further constrain the optical models and allow for higher-sensitivity measurements.

TRANSIENTS: With science entering a new era of multi-messenger astronomy, and with most multi-messenger astronomy events being driven by nuclear physics, there is now a major opportunity for nuclear science to provide the nuclear physics needed to interpret these observations. The astronomical objects of interest are predominantly transient events such as stellar explosions.

A galactic core-collapse supernova would be a major scientific opportunity, and nuclear physics needs to be understood to take advantage of neutrino, gravitational wave, and electromagnetic observations. While the weak interaction rates that shape neutrino signals have been studied successfully near stability, sensitivity studies have shown important contributions from neutron-rich nuclei that now come into reach for charge-exchange reaction measurements at FRIB using the AT-TPC and the HRS. Complementary to that are the necessary advances in understanding the nuclear physics of supernova nucleosynthesis using a broad range of nuclear accelerator facilities discussed above, and that shape light curves, remnant abundances, gamma-ray emissions, and presolar grain signatures.

Neutron star mergers are another prime target of multi-messenger astronomy and of key importance for nuclear physics as both, major sites of heavy element nucleosynthesis (see above) and as probes of nuclear matter (see below). Interpreting multi-messenger transient signatures of neutron star mergers is key. This includes the light curve and spectral features of the associated kilonova event that is directly powered by the nuclear decay of neutron-rich nuclei produced in the r-process. Addressing the underlying nuclear physics using complementary radioactive

beam facilities at FRIB and Argonne National Laboratory (see discussion above) and novel nuclear theory approaches will be critical. This will be especially timely in light of expected advances in sensitivity at LIGO, and new ground- and space-based capabilities to detect and observe kilonovae, including the new James Webb Space Telescope.

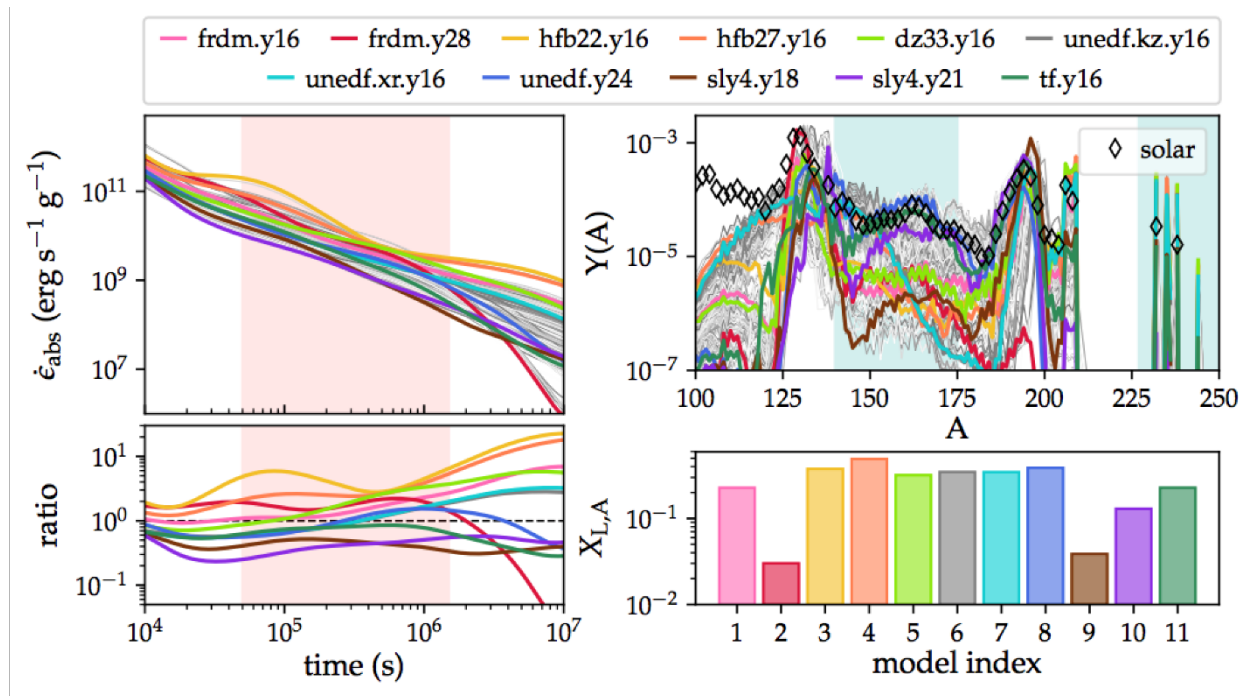


Figure 3.5: Impact of different predictions for unknown nuclear masses (different colors) on the nuclear astrophysics of neutron star mergers, including energy generation as function of time powering a kilonova (left panel) and the abundance distribution of the new nuclei produced in the r-process (right panel). Argonne and FRIB experiments will pin down the important nuclear masses, greatly reducing uncertainties [Bar21].

X-ray bursts occur on the surface of accreting neutron stars. With their high frequency of observation in our Galaxy (more than a hundred systems, many bursting many times a day) X-ray bursts offer a unique portal to probe neutron-star and dense-matter properties. New experimental capabilities now offer a unique opportunity to address, in the coming decade, most of the nuclear-physics uncertainties in the rapid proton capture process (rp process) and together with advances in multi-D modeling enable precision analysis of observations. Similarly, it can be expected that the nuclear physics uncertainties of classical novae, occurring on accreting white dwarfs and powered by a milder form of the rp process, can be fully addressed. This will allow for unambiguous identification of presolar grains as being truly of nova origin. Unique isotopic signatures from nova grains will provide insight into the radiation transport and detailed composition of white dwarf progenitors.

In particular, improvements to experimental techniques and beam intensities will allow for access to critical rp-process reactions in the coming decade, such as $^{30}\text{P}(p,\gamma)^{31}\text{S}$, $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$, $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$, and $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$. Detailed and spectroscopic charged-particle reaction studies will continue to provide data not only to refine astrophysical models, but also to refine nuclear theory, for example driving improvements in statistical model predictions of reaction rates on nuclei in the $A \sim 20\text{--}100$ region relevant to explosive binary systems. Another major opportunity is determining the impact of low-lying isomers on the element synthesis and energy generation of rp-process events. Such isomers can be populated either through thermal excitation in the environment, or as the product of a decay.

As many rp-process nuclei lie near the $N=Z$ line, low-lying isomers often have a substantial spin difference from the ground state, as is the case with ^{26}Al ; these “astromers” [Mis22] have the potential to significantly impact the nucleosynthetic networks in explosive astrophysical scenarios. Stellar enhancement factors (effective beta decay rates) of the mixed isomer and ground state populations need to be experimentally verified, as do reaction rates such as proton capture on the isomer as well as the ground state.

To address the open questions in rp-process reaction rates for both X-ray bursts and novae, access to intense, light-mass, proton-rich beams is necessary, along with a complementary suite of experimental instruments and techniques. Isomeric beams, which allow for first studies of the reaction rates on astromers, can be produced either via fragmentation and charge-breeding to remove the shorter-lived component or through selective in-flight reactions to preferentially populate the isomer. This requires a program at both the Argonne ATLAS RAISOR facility and the FRIB ReA facility to take advantage of the complementary beams produced at each facility. Constraining the critical reaction rates for identification of nova presolar grains will take advantage of exotic beams from FRIB, stable and in-flight beams from ATLAS, and continued work at ARUNA in-flight beam facilities such as Resolut and TriSol. A multipronged effort of direct and indirect reactions at FRIB, ATLAS, the ARUNA laboratories, and elsewhere, utilizing an entire suite of state-of-the-art experimental systems (such as those listed earlier), is needed to fully address the remaining open questions regarding explosive proton-rich nucleosynthesis.

With FRIB and, in particular, the FRIB400 energy upgrade there is also an opportunity to map basic properties of the nuclei that make up the crust of accreting neutron stars. This will enable accurate modeling of nuclear heating and cooling, and transform observations of X-ray bursts and cooling neutron stars in transiently accreting systems into probes of unique dense matter physics. This is particularly timely in light of the advanced capabilities of current and future X-ray telescopes such as ATHENA, XRISM, or eXTP. This includes probing neutron superfluidity, an unidentified heating process, density-induced fusion reactions and screening, neutron transfer between nuclei in the solid crust, and the properties of nuclear pasta, a unique form of matter making up most of the material of neutron star crusts. This will also guide investigations of the mysterious non-nuclear heat source that appears to be present in some systems, and can illuminate cooling mechanisms and properties of the high-density neutron star core. With the extended reach of FRIB400, FRIB will be able to probe the limits of existence of neutron-rich nuclei up to potentially $A \sim 100$ and thus produce and study all nuclei relevant for nuclear processes in the outer crust of neutron stars. Of particular importance will be mapping out the nuclear mass surface and nuclear structure properties such as spherical and deformed shell and subshell closures, which have been shown to affect the nuclear processes, composition, and thermal transport properties of accreted crusts. Charge exchange using the HRS and beta-decay measurements with the FDS will probe important weak interaction strengths that govern most of the relevant nuclear transformations and neutrino emissions, while fusion reaction measurements will explore how our understanding of nuclear fusion changes with neutron richness.

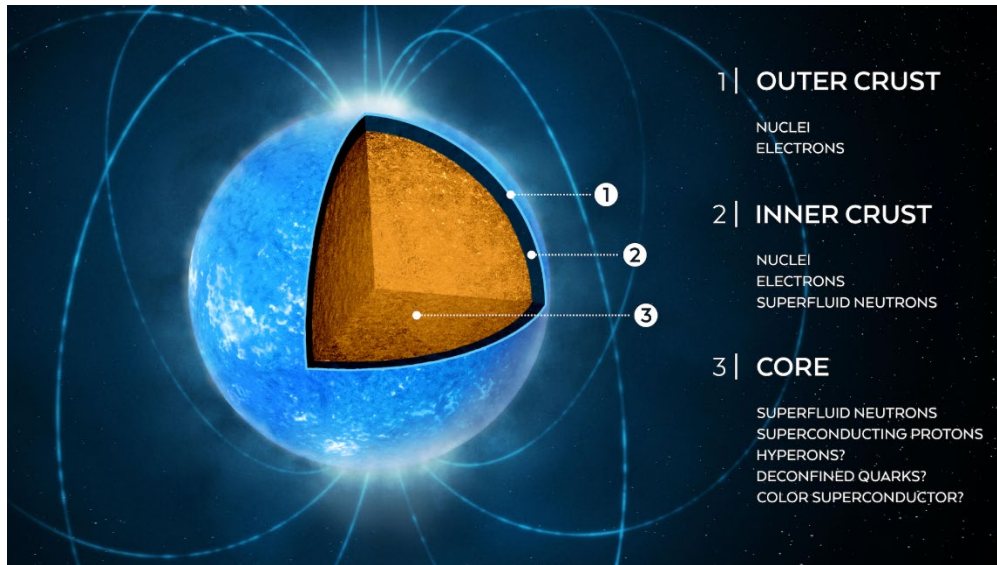


Figure 3.6: There is a major opportunity in nuclear astrophysics to unravel the nature of the interior of neutron stars using laboratory nuclear physics experiments, theory advances, and various observational probes. This will provide fundamental insights into the properties of matter at extreme densities [Wat16].

DENSE MATTER: We are approaching our vision of an accurate equation of state of dense matter which works from low density to high, from the crust of a neutron star to the core. Within the next 5-10 years, we have the opportunity to constrain the crucial aspects of the equation of state. More precise measurements for symmetric matter are necessary and within reach, as are stronger symmetry energy constraints. These can be obtained in heavy-ion collision measurements, which probe densities 1.5 to 2.5 times normal nuclear density. A white paper titled “Dense Nuclear Matter Equation of State from Heavy-Ion Collisions” emanating from the December 2022 workshop at the Institute for Nuclear Theory will soon be published detailing the opportunities in this field. Heavy-ion collision observables, such as particle yield ratios, the flow patterns of particles, and collective excitations of nuclei, must be compared to theoretical predictions, such as those from dynamical transport simulations of heavy ion collisions, to extract equation-of-state parameters. These require measurements at existing facilities (including RHIC beam energy scan), facility upgrades (including FRIB400, HRS), detector investments, transport model improvements, support for ARUNA labs, and continued investment in the training of young scientists. The value of such investments is multiplied when coupled to astronomical observations, such as properties of neutron stars and the signatures of neutron star mergers. The dynamics of such mergers affect the ejection of neutron star material for nucleosynthesis and the fate of the post-merger object. The new ability to observe gravitational waves from neutron star mergers as well as the light emitted during and after the merger using precision terrestrial measurements, has opened a new synergy between nuclear science and astronomy that is rapidly increasing our understanding in both fields.

The role of heavy-ion collision measurements is crucial and unique in constraining the equation of state. Heavy-ion collisions allow exploration of a wide range of densities, and offer multiple observables, which must all be simultaneously described by theoretical models. As the only type of probe that spans density so broadly, heavy-ion collisions act as a link between all constraints on the equation of state. To reach higher densities, closer to neutron star matter, faster heavy ion beams of exotic nuclei are necessary, and can be achieved with the FRIB400 upgrade. The High Rigidity Spectrometer and new state of the art particle detectors will be crucial in capitalizing on this facility.

CROSS CUTTING: Connecting and forming a community of multiple disciplines and subfields will be more important than ever for nuclear astrophysics in the multi-messenger era. The scientific goals of the field cannot be accomplished in isolation. A center that fulfills the role of JINA-CEE in this era, such as the proposed Center for Nuclear Astrophysics across Messengers (CeNAM), will be critical to form these connections, and include the full range of communities needed, including nuclear experiment and theory, astrophysics, computational modeling, observations across the entire multi-messenger spectrum, asteroseismology, and cosmochemistry. A center will also play an important role in fostering international connections to take advantage of complementary capabilities across the world that are especially important for nuclear astrophysics due to the breadth of the required activities, and it will provide important opportunities for workforce development and enhancing the DEIA goals of the field. Advances are also needed in evaluating, curating, and disseminating data across field boundaries. This includes nuclear data that must be transformed into data that can be used in astrophysical models in a timely fashion to accelerate progress and discovery potential. The inclusion of uncertainties is particularly important as we enter an era where astrophysical models are confronted with detailed observations in a quantitative way. Similarly, astrophysical model data and observational data need to be available for nuclear scientists to identify open nuclear physics questions and to design the most impactful experiments.

NEEDS TO REALIZE OPPORTUNITIES

A common thread in taking advantage of the exciting opportunities in experimental nuclear astrophysics in the coming decade is the need to leverage the capabilities of a very broad range of national facilities and ARUNA laboratories - including a very broad range of experimental capabilities within each. This need for a broad range of complementary approaches is an intrinsic feature of this field and dictated by the breadth and complex interplay of the nuclear physics needed for astrophysics, and by the experimental challenges to measure, for example, extremely small cross sections or dense matter properties that require complementary approaches to succeed. The optimal operation of FRIB and ATLAS, investments in ARUNA facilities, and support for key national laboratory facilities are therefore of particular importance for every aspect of nuclear astrophysics.

While investments in workhorse devices are important for the broader community, future success also requires that funding be allocated to ensure the health of research groups pursuing these novel techniques. The broader nuclear astrophysics community is where new, novel ideas are born. To ensure the health of the program, further investment should be made in supporting not only device and equipment development, but also in supporting personnel and research from the level of students and postdocs through research scientists, technical staff, and faculty throughout the program, particularly for university groups and ARUNA laboratories, whose potential cannot be fully realized without healthy research teams.

Making the most of the wealth of opportunities available in the next decade, from new experiments, new nuclear theory developments, new observations, and enhanced computing, will require corresponding investments in theoretical and computational nuclear astrophysics. The physics needed, for example, the complex flavor physics of quantum mechanically entangled seas of neutrinos and the responses of nuclear matter at 4-6 times nuclear density, extends well beyond what one knows from terrestrial experiments. Both the range of the physics and the exotic conditions under study pose challenges for theory. To meet these challenges, investments in theory should enhance support for traditional single-investigator grants, but also enhance support for collaborative networks of many forms.

Addressing the challenges in nuclear astrophysics and taking advantage of the extraordinary opportunities to advance the field in the coming decades will require pushing experimental nuclear physics capabilities to the limit

and upgrading facilities and instrumentation to take full advantage of the novel technical capabilities in the field. The FRIB400 upgrade will be important to reach the extremely unstable nuclei of the r-process and the crusts of neutron stars and to probe dense matter at neutron star densities. With the forthcoming completion HRS and GRETA, an advanced FRIB decay station will be important for r-, i-, and rp-process studies at FRIB. The FRIB ReA12 upgrade and the ISLA spectrometer will be important for indirect astrophysical reaction rate measurements. At ATLAS, the completion of the nuCARIBU and N=126 factory will provide important, complementary, rare isotope capabilities especially for r-process nucleosynthesis. Given the breadth of nuclear physics needed in astrophysics, and the challenging nature of nuclear astrophysics experiments, support for detector development and upgrades at all facilities, including national user facilities and ARUNA laboratories, is critical. For reaction measurements on longer lived radioactive isotopes, FRIB harvesting, other isotope production capabilities, and facilities to fabricate targets are needed. A heavy ion storage ring, intersecting with a neutron beam, would open up novel opportunities to measure neutron induced reactions on short lived radioactive nuclei.

Investments are also needed to enhance access to cutting-edge high-performance computing resources as well as machine-learning and quantum computing platforms. This investment should enhance support for traditional single-investigator grants, but also enhance support for collaborative networks of many forms. To properly describe the events of interest to nuclear astrophysics, one needs to marshal expertise in, for example, the weak interaction physics that governs the transport of energy, lepton number, and entropy in events like NS mergers and CCSN; in the nuclear equation-of-state physics that determines the structure of newborn and colliding neutron stars and the dynamics of their in-spiral, deformation, and gravitational wave generation; and in the nuclear reactions networks of the explosive nucleosynthesis. Up-to-date, statistically rigorous sensitivity studies based on these reaction networks, such as those enabled by STARLIB and REACLIB nuclear reaction rates databases, are also essential. It will be important to expand these interdisciplinary databases to all relevant nuclear data, including weak interaction data, fission data, and nuclear properties.

Support for single investigator efforts are vital building blocks to achieve the understanding we seek, but no single investigator or small group has the breadth of theory expertise or the numerical modeling capability required to tackle such multi-scale, multi-physics problems alone. In the past decade, nuclear astrophysics theory and computation has benefited greatly from extended collaborations such as the TEAMS SciDAC collaboration, the N3AS Physics Frontier Center, the N3AS and NP3M Focused Research Hubs, the NNHDM Topical Collaboration and related collaborations such as EXASTAR, funded by the Exascale Computing Program, and MUSES and BANDcamp, funded by the NSF Cyberinfrastructure program. These collaborations, in various combinations, have brought together the diversity of expertise needed to advance our understanding of nuclear astrophysics. These funding opportunities provided critical resources that were not available in traditional single-PI grants: robust postdoctoral funding, computational resources, and collaborative teams dedicated to addressing frontiers in nuclear theory. These collaborations also give back to the community, providing training for young scientists and open-source computer codes which can be used to leverage future science. For this reason, collaborative funding mechanisms such as the DOE SciDAC and Topical Collaboration programs, the NSF Physics Frontier Center and Focused Research Hub programs are critical to make the transformative progress needed in the next decade to fulfill the opportunities that will present themselves. For this reason, we strongly support enhanced funding for collaborative programs like these, so that the needs of nuclear astrophysics, as well as the corresponding needs of other areas of nuclear theory, can all be met.

The need for collaborative networks does not stop at the edges of nuclear astrophysics theory or nuclear astrophysics experiment. Strongly-interacting systems, from neutron star mergers to core-collapse supernovae to

heavy-ion collisions, demand coordinated collaboration between experimentalists, astronomers, theorists, cosmochemists, and gravitational physicists. The experimental and observational signatures of these systems cannot be immediately connected to the parameters of the effective interactions which we use to model their evolution. Each of the intermediate steps requires its own expertise, best provided by coordinated efforts. In the past decade, the entire nuclear astrophysics community has benefited greatly from the Joint Institute of Nuclear Astrophysics and its successor, the Joint Institute of Nuclear Astrophysics Center for the Evolution of the Elements, both by building coordinated research networks but also by supporting a broad program of multi-disciplinary conferences and workshops. These meetings serve not only to keep the broad nuclear astrophysics community informed about progress across the community, but also as incubators for future research networks by connecting disparate researchers with common interests. We therefore think that continued support for programs that fulfill the role of JINA and JINA-CEE, such as CeNAM, is important if we are to make the most of the opportunities the next decade will provide.

Nuclear astrophysics is an interdisciplinary field and specific advances in fields outside nuclear physics are needed. Many of these advances are described in the Astro2020 Decadal Survey [Tim19]. It will be important for the nuclear physics community to engage in these developments, for example, in providing additional scientific motivation and guidance on technical requirements to meet the needs of nuclear astrophysics. Important needs outside of nuclear physics include advances in observations, such as large scale spectroscopy, including ultraviolet spectroscopy (e.g. LUVUOIR), to detect elements of particular importance or capabilities to constrain isotopic compositions; improved atomic data for heavy elements to bring higher fidelity to spectroscopic models; an enhanced MeV gamma-ray observation capabilities such as COSI to detect nuclear decay gamma-rays in space; advanced X-ray observatories to probe neutron stars; next generation gravitational wave detectors; asteroseismology; and transient sky surveys. In cosmochemistry, advances in stardust collection and isotopic analysis will be important.

A more in-depth overview of progress and opportunities in nuclear astrophysics, including relevant sidebars, can be found in the recent whitepaper [Horizons: nuclear astrophysics in the 2020s and beyond](#) [Sch22].

BIBLIOGRAPHY

[ALI22] M. Aliotta *et al.*, J. Phys. G 49, 010501 (2022).

[ARUNA22] [The ARUNA collaboration](#).

[BAI19] L. Baiotti, PPNP 109, 103714 (2019).

[Bar21] J. Barnes *et al.*, Astrophys. J. 918 44 (2021).

[BOR20] The Borexino Collaboration, Nature 587, 577 (2020).

[Bur22] J. Burggraf and A. Zylstra, Frontiers in Physics 10, 993632 (2022).

[BUR21] G. F. Burgio *et al.*, PPNP 120, 103879 (2021).

[Chu19] T. E. Chupp *et al.*, Rev. Mod. Phys. 91, 015001 (2019).

[COL20] M. Colonna, PPNP 113, 103775 (2020).

[Cow21] J. J. Cowan *et al.*, Rev. Mod. Phys. 93, 015002 (2021).

[Cyb10] R. Cyburt *et al.*, Ap. J. Suppl. 189, 240 (2010).

- [DEB17] R. J. deBoer *et al.*, Rev. of Mod. Phys. 89, 035007 (2017).
- [FDS] [The FRIB Decay Station](#).
- [HRS] [HRS – A high rigidity spectrometer for FRIB](#), Whitepaper authored by the nuclear science community.
- [Hor19] C. Horowitz *et al.*, J Phys G 46, 083001 (2019).
- [ILI15] C. Iliadis *et al.*, J. Phys. G 42, 034007 (2015).
- [ISLA] [ISLA Isochronous Separator with Large Acceptances Recoil Separator for Rea12](#), White paper on the science case and proposed technical solution.
- [Lan21] K. Langanke *et al.*, Reports on Progress in Physics 84, 066301 (2021).
- [LYN22] W. G. Lynch and M. B. Tsang, Phys. Lett. B 830, 137098 (2022).
- [MCI19] A. B. McIntosh and S. J. Yennello, PPNP 108, 103707 (2019).
- [Mei18] Z. Meisel *et al.*, J Phys G 45, 093001 (2018).
- [Mis22] G. W. Misch *et al.*, ApJS 252, 2 (2021).
- [Mum16] M. Mumpower *et al.*, JPPNP 86, 86 (2016).
- [ORE21] G. D. Orebi Gann *et al.*, Annu. Rev. Nucl. Part. Sci. 71, 1 (2021).
- [Orf22] R. Orford *et al.*, Phys. Rev. C 105, L052802 (2022).
- [RAISOR] <https://www.anl.gov/atlas/inflight-radioactive-beams>
- [Rat19] A. Ratkiewicz *et al.*, Phys. Rev. Lett. 122, 052502 (2019).
- [ROC18] X. Roca-Maza and N. Parr, PPNP 101, 96 (2018).
- [SAL13] A. Salaska *et al.*, ApJ Supp. Ser. 18, 18 (2013).
- [Sch22] H. Schatz *et al.*, J. Phys. G 49, 110502 (2022).
- [SOLARIS] [SOLARIS White Paper](#), Editors: B. P. Kay, C. R. Hoffman, and A. H. Wuosmaa (2018).
- [Spi19] C. Spitaleri *et al.*, EPJA 55, 161 (2019).
- [SUB20] S. Subedi *et al.*, ApJ 898, 5 (2020).
- [Tim19] F. Timmes *et al.*, [Astro2020: Decadal Survey on Astronomy and Astrophysics, science white papers, no. 2](#); Bulletin of the American Astronomical Society, Vol. 51, Issue 3, id. 2 (2019).
- [Tri14] R. E. Tribble *et al.*, Reports on Progress in Physics 77, 106901 (2014).
- [Wat16] A. L. Watts *et al.*, Rev. Mod. Phys. 88, 021001 (2016).
- [WEI20] C. Weinberger *et al.*, Astron. Astrophys. 638, A83 (2020).
- [WOL22] H. Wolter *et al.*, PPNP 125, 103962 (2022).

[WP_NFS] Whitepaper from the DNP Fundamental Symmetries, Neutrons, and Neutrinos Town Meeting (2023).

[WP_QCD] Whitepaper from the DNP Hot and Cold QCD Town Meeting (2023).

4 FACILITIES, DETECTORS, AND UPGRADES

INTRODUCTION

As stated in the preamble to the resolutions of the Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics, nuclear science is at a unique moment where past initiatives have laid the foundation for tremendous progress and delivery of world-class science in the next decade. To achieve its full discovery potential through a robust research program, the field requires the continued upgrade of its facilities and instruments. In this chapter, the status of the user and university-based facilities is briefly reviewed, and upgrades are presented together with plans for new instruments and upgrades to existing ones.

One of the specificities of the field of low-energy nuclear science addressed in this Town Hall meeting is the many opportunities it provides for hands-on education where students are associated with every step of the research enterprise; from the development of an idea to the writing of a proposal, from the design and construction of an apparatus to the successful conduct of a measurement, from the analysis of the data to the presentation and discussion of the results in a scientific publication. Thus, this field plays an important role in the development of the nuclear science of the future. It will continue to do so, given adequate support.

FACILITY FOR RARE ISOTOPE BEAMS

The DOE funds operation of the Facility for Rare Isotope Beams (FRIB), the nation's new flagship user facility with more than 1600 registered users. The primary research mission is to understand the nature of the nuclear force, the structure of atomic nuclei, the origin and evolution of chemical elements in the Universe, and to contribute to societal applications by using beams of rare isotopes. FRIB is designed to produce rare isotopes in-flight from beams of stable ions ranging from helium up to uranium, with energies of 200 MeV/u for uranium and higher for lighter ions, and a beam power of up to 400 kW. The facility has been designed having in mind the possibility to upgrade to higher primary beam energies.

FRIB user operation for science successfully started in 2022. Already in its first call for proposals, FRIB has seen a very high demand for beam time from the user community. Operations at a 5000 hour/year level is critical for leveraging the investments made in FRIB and to fully exploit the science opportunities it enables.

FRIB provides world-unique research opportunities with the availability of fast, stopped, and reaccelerated beams, over a wide range of energies: from a few keV/u to at least 200 MeV/u for rare isotopes produced in-flight. Stopped-beam facilities allow for trapping and laser spectroscopy experiments as well as for precision decay spectroscopy. Facilities for reaccelerated-beam experiments at astrophysical energies include the recoil separator SECAR. Fast beam instruments for reaction, nuclear decay, and spectroscopy studies include the S800 magnetic spectrograph that can be coupled with the GRETINA/GRETA gamma tracking array, and the new FRIB Decay Station initiator (FDSi).

To support a strong science program with fast beams, FRIB's experimental areas have been optimized with the recent addition of a dedicated vault for decay studies. A new large high bay has been completed to house the future High Rigidity Spectrometer (HRS).

FRIB's beam stopping capability has been enhanced with the addition and successful operation of an advanced cryogenic gas stopper (ACGS) for improved beam purity and higher beam rates. A cyclotron gas stopper for light ions has been successfully commissioned and awaits beam line connection to the experimental areas. A Batch-Mode-Ion Source (BMIS) has been added that provides beams of stable and long-lived isotopes for stopped and reaccelerated beam experiments in areas where FRIB can be unique, enabling science in parallel to fast-beam experiments.

An important upgrade, ReA6, of the ReA post accelerator was completed with the addition of a cryomodule and a new shielded experimental vault with two user beam lines, one accommodating a new solenoidal spectrometer for reaction studies, SOLARIS. ReA6 provides beam energies of 6 MeV/u for uranium and has already been used for a series of successful user experiments. ReA can be upgraded to higher energies by adding cryomodules to provide beams best suited for transfer reactions, multiple Coulomb excitations, massive transfer in deep inelastic scattering, or fusion reactions, for example, with the proposed Isochronous Spectrometer with Large Acceptance (ISLA).

4.1.1 FRIB SCIENTIFIC INSTRUMENTATION

FRIB enables users to address a wide range of important topics at the forefront of nuclear science. Successful science requires state-of-the-art scientific instrumentation aligned with identified science drivers and increasing facility capabilities. Upgrades and new major instruments such as GRETA or HRS will maintain FRIB's world-leading role and leverage the large initial investment.

With the beginning of user operation, FRIB and its users are making best use of existing state-of-the-art scientific instrumentation at the laboratory, and instruments and detector systems available within the FRIB user community while new scientific instrumentation is being developed and employed. Engaging FRIB external users and institutions in the development of, or planning for, new scientific instrumentation is a priority. It leverages expertise across the community and supports the FRIB mission. Realization of Research Capital Equipment (RCE) projects for new scientific instrumentation under external leadership is already very successful.

The FDSi, an RCE project led by ORNL, has been used successfully in the very first FRIB experiments. It is also the first step towards a full, new FRIB decay station (FDS). At present, the FDSi accommodates and augments, in a versatile manner, community-owned detectors for decay studies of the most exotic nuclei. The GRETA project has received CD2/3 and is under construction. It will be delivered to FRIB in 2 phases (CD-4a and CD-4) to enable early science. Phase-1 includes delivery of the full electronics, computing, and mechanical subsystems and initial detector modules, followed by Phase-2, with procurement of the balance of detector modules over several years. It is planned to be able to use up to 20 GRETA quad detector modules and the electronics in a modified GRETINA frame at the S800 spectrograph to increase the gamma-ray detection efficiency for fast-beam experiments prior to completion of the HRS described below. This approach will enable more science output per beam time and increase further the reach into nuclei furthest away from stability. The HRS project, a High Rigidity Spectrometer for a wide range of nuclear reaction and structure studies that is matched to FRIB beam rigidities, has CD-1 approval and the preliminary design is advanced. The recoil separator for nuclear astrophysical reaction studies, SECAR, funded jointly by DOE and NSF, is operational and first experiments with stable and long-lived isotopes have been conducted. SOLARIS, the SOLenoid spectrometer Apparatus for Reaction Studies, realized as an RCE project led by ANL, has been used for reaction studies in both the AT-TPC mode and the Si-Array mode with ReA6 beams.

Other RCE projects underway which increase FRIB's science reach and scope include the addition of highly-sensitive resonance ionization spectroscopy to FRIB's BECOLA facility with RiSE, a project led by MIT, and SALER, a Superconducting Array for Low-Energy Radiation dedicated to weak interaction studies through the precision detection of sub-keV nuclear recoils, a project led by the Colorado School of Mines.

Additional information on FRIB instrumentation can be found at:

<https://frib.msu.edu/users/instruments/index.html>

4.1.2 FRIB400

The tremendous discovery potential of FRIB can be further extended with an energy upgrade of the FRIB linear accelerator to 400 MeV/u for uranium and to higher energies for lighter ions (FRIB400). The science potential of FRIB400 was articulated in the community's FRIB400 Whitepaper [FRIB400]. In addition to transforming certain reaction studies, FRIB400 will allow new science opportunities thanks to the increased rare-isotope production rates and transmission, benefitting all experiments, and significant additional luminosity gains when using thicker secondary targets for in-beam experiments using FRIB's fast beams. An increased reach towards the neutron dripline and orders-of-magnitude beam purity increases for neutron-deficient nuclei promise new science opportunities across the nuclear chart.

In anticipation of this science potential, space was provided, at the facility design phase, in the FRIB tunnel for an energy upgrade of the accelerator to 400 MeV/u for uranium. Eleven cryomodules, with five superconducting elliptical cavities each, would provide the required accelerating fields. Much of the technology has been proven, two bare prototype cavities were tested multiple times [McG21], exceeding the performance specifications of FRIB400, and a fully dressed cavity is ready for cold testing. This upgrade can be implemented in a staged approach during regular shutdowns with no major interruption of the FRIB science program. At each stage, the gain in primary beam energy will translate into an increased science potential. The FRIB fragment separator and the beam distribution to key detector systems are well matched to the upgrade. Instruments, such as the HRS, have been designed to be compatible with this upgrade.

With the technology proven and the team in place, FRIB400 is ready for implementation within a staged approach, without major interruption of the user program, and with science gains at every stage of the energy upgrade.

THE ATLAS FACILITY

The ATLAS facility is a US DOE national user facility for nuclear physics research at low energies. These energies, in the vicinity of the Coulomb barrier, cover the energy domain where nuclear reactions occur in the cosmos. ATLAS provides a wide range of beams for nuclear reaction and structure research to a large community of users from the US and abroad. The full range of all stable ions can be produced, accelerated in the world's first superconducting linear accelerator for ions to energies of 10 - 20 MeV per nucleon, and delivered to one of several target stations. The facility was enhanced a decade ago with the Californium Rare Isotope Breeder Upgrade (CARIBU) which allows it to also produce world-unique beams of neutron-rich rare isotopes of interest to nuclear structure and astrophysics as well as for societal applications such as next generation nuclear reactors and nuclear forensics.

4.1.3 RESEARCH PROGRAMS

The ATLAS research programs focus on the key questions which are central to our understanding of matter and on the description of the astrophysical processes which generate energy and produce elements in the stars. These areas of research have been endorsed in several major reviews of the science. Specific issues being addressed include 1) the quantum shell structure of nuclei, 2) the evolution of nuclear structure as a function of neutron excess, 3) exotic decay modes, 4) masses of exotic nuclei, 5) fundamental symmetries, 6) nuclear reactions of astrophysical importance, 7) properties of the heaviest nuclei, and 8) applications of nuclear science. ATLAS hosts several unique state-of-the-art instruments to perform this research efficiently. They include devices developed at ATLAS and devices built by ATLAS users that are stationed at the facility to take advantage of the unique beams ATLAS can provide.

4.1.4 PROGRESS SINCE THE LAST LRP

The ATLAS accelerator has been regularly upgraded to remain at the forefront of accelerator technology. Upgrades since the last LRP have focused on increasing the intensity and purity of radioactive beams, increasing the beam time on target, and adding experimental capabilities to take advantage of these more intense beams. Purity of the unique reaccelerated neutron-rich beams from CARIBU was improved by the addition of an EBIS ion source to increase the charge state of beams from CARIBU for injection into ATLAS, making these beams essentially free of stable beam contamination. The RAISOR separator was installed to improve the intensity and purity of the light in-flight radioactive beams. The last cryostat of ATLAS was refurbished with eight high-performance quarter-wave resonators, and a new digital low-level RF system. As a result, the maximum energy of the facility was increased by 4 MeV/u for mid-mass nuclei. The reliability of the accelerator now reaches 95%, thanks to a number of upgrades such as the addition of a novel highly redundant, solid-state amplifier driving the RFQ section of the linac and a new radiation interlock system. Experimental equipment has also been significantly improved with the digitalization of the GAMMASPHERE detector array acquisition system which has improved counting rate capabilities by roughly an order of magnitude. This upgrade, coupled to the new gas-filled spectrometer AGFA, yields the most powerful setup to study the structure of the heaviest nuclei. A new low-background experimental area was also added to improve the sensitivity of decay spectroscopy experiments with unaccelerated CARIBU beams.



Figure 4.1: A string of superconducting cavities and focusing solenoids developed for a recent intensity upgrade of the ATLAS facility.

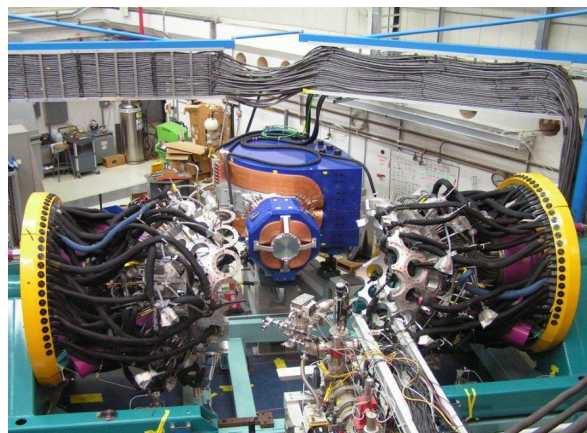


Figure 4.2: The GAMMASPHERE germanium detector array located at the focal plane of the AGFA gas-filled spectrometer.

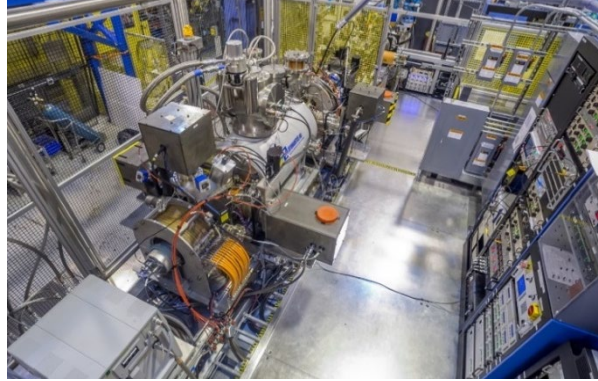


Figure 4.3: The EBIS ion source used to increase the charge-state of the rare neutron-rich isotopes obtained from the CARIBU facility for acceleration through the ATLAS linac.

4.1.5 OPERATIONS AND ON-GOING FACILITY UPGRADES

The ATLAS facility delivers about 6000 hours of beam time per year to its users with high reliability, and an additional 2000 hours or more per year of unaccelerated neutron-rich beams from CARIBU. Even with 8000 hours of beam time delivered per year, the facility is highly oversubscribed and can only accept about one third of the proposals submitted to the PAC. An on-going upgrade of the facility, the ATLAS Multi-User Upgrade, will enable the delivery of ATLAS beams to more than one experiment at a time, thereby significantly increasing the effective number of beam time hours delivered, and allowing the facility to accept more of the experiments proposed by the scientific community. The intensity of the CARIBU beams will also be increased by the nuCARIBU upgrade where an intense neutron-generator will be installed to produce fission products via neutron-induced fission. Thus, nuCARIBU will replace the ^{252}Cf spontaneous fission sources in use at CARIBU and provide a roughly one order-of-magnitude gain in intensity for most fission products.

In addition, new capabilities are being added to gain access to new regions of rare isotopes which have escaped detection so far. These new isotopes, mostly very neutron-rich isotopes of the heavier elements, are critical to our understanding of the formation of the heavy elements in the cosmos. However, the reaction mechanisms typically used in existing facilities do not produce these in sufficient amounts to enable their study. A new reaction mechanism, coupled to the techniques developed at ATLAS for the CARIBU facility, will allow these new isotopes to be produced and separated with sufficient intensity to enable first studies of their properties. This upgrade, the so-called “N=126 factory”, named after the neutron number of the isotopes of interest, will provide access to this so far unexplored region, starting in FY2023.

THE ARUNA FACILITIES

ARUNA facilities provide a unique set of nuclear probes that are often not available at national facilities. They offer flexibility and quick response to research developments and challenges and usually have the ability to provide beam time for the long durations required by specific experiments such as those in nuclear astrophysics, where cross sections are low, or those in fundamental symmetries, where high statistics and extensive studies of systematics are the norm.

Accelerator Facility	Flagship Devices, Capabilities
Florida State Univ. (FSU) 9 MV Tandem + 8 MV Superconducting Linac Booster	Light- and Heavy Ion beams with $A < 60$ RESOLUT in-flight RIB facility: exotic beams between mass 6 and 30 ANASEN: Active-target detector for nuclear astrophysics studies High-resolution SE-SPS spectrograph for precision spectroscopy Clarion-2 Ge-detector array for nuclear structure studies <i>Planned upgrade:</i> Adding cryostats to SC Linac to reach 13 MV potential
Hope College (HC) 1.7 MV Tandem	Ion-beam analysis setup, Materials analysis
James Madison University (JMU) Medical Electron Linac X-ray digital imager	Electron Beams from 5 to 14 MeV for materials analysis Bremsstrahlung Photons up to 15 MeV for programs in nuclear structure and nuclear astrophysics
Ohio University (OU) 4.5 MV Tandem	Beams of p,d, ³ He, heavy ions, 30-m-long neutron time-of-flight setup, particularly well equipped for time-of-flight experiments and neutron detection <i>Planned upgrade:</i> FAST Neutron-source beamline, SNICS-II ion source
Texas A&M Univ. (TAMU) K-150, K-500 Cyclotrons, ECR ion sources	MARS recoil spectrometer, production and separation of radioactive beams, Nimrod high-efficiency multi-particle detector, Precision on-line β -decay γ -detector system, MDM spectrometer, FAUST-QTS, HYPERION Ge-detector array, DAPPER, TAMU-trap, TexAT, Radiation effects facility
TUNL-HIγS 1.2 GeV Electron Storage Ring	World's most intense Compton γ -ray source, 1.2-GeV e^- -storage ring with Free Electron Laser (FEL), γ -ray beam through Compton-backscattering of FEL photons, Linearly and circularly polarized quasi-monoenergetic γ -ray beams, program in γ -ray induced astrophysical reaction rates, nuclear structure, and nucleon structure (low-energy QCD) <i>Planned upgrade:</i> Increase capacity of FEL wigglers, increase photon energy to 150 MeV, increase g-ray beam intensity x100 with optical cavity pumped with external laser
TUNL-LENA 2 MV Singletron, with 2 mA pulsed beam 230 kV ECR source, with 20 mA pulsed beam	Very high intensity, pulsed beams for nuclear astrophysics, high-resolution HPGe-detector inside NaI(Tl) annulus, surrounded by muon veto shield. Program to measure proton and α -particle induced reactions important for stellar evolution and explosions
TUNL-Tandem 10 MV Tandem	Secondary neutron beams, Split-Pole high-resolution magnetic spectrograph, versatile implantation facility for fabricating targets of noble gases and refractory elements, programs to measure the nuclear structure of levels important for globular cluster nucleosynthesis and galactic radioactivity, few-nucleon reactions, neutron-induced fission <i>Planned upgrade:</i> Ion source upgrade x5 intensity in light-ion beams, heavy-ion beams
Union College (UC) 1.1 MV Tandem	PIXE, PIGE, Rutherford Scattering facilities
Univ. of Kentucky (UK) 7 MV single-ended vdG	In-flight production of mono-energetic neutrons Shielded setup for high-resolution γ -ray spectroscopy after inelastic neutron scattering; neutron time-of-flight capabilities
Univ. of Massachusetts Lowell (UML) 5.5 MV single-ended vdG 1 MW Research Reactor	In-flight production of mono-energetic, pulsed neutron beams Programs in neutron detector development Programs in neutron and segmented-Ge detector development

Univ. of Notre Dame (ND) 11 MV Tandem "St. Ana" 5 MV Pelletron 3 MV tandem for applications	TriSol in-flight radioactive beam facility Accelerator mass spectrometry with ion source and gas-filled spectrometer St. George recoil separator for astrophysical reaction rate measurements Program with PIXE, PIGE, AMS RMS and radiochemistry applications <i>Planned Upgrade:</i> commissioning of Split-Pole spectrograph at 11 MV Tandem
Univ. of Notre Dame (ND) "CASPAR" 1MV VdG at SURF	Deep-underground accelerator for background-free low-energy nuclear astrophysics experiments
Univ. of Washington (UW) 9 MV Tandem	World-record production of ${}^6\text{He}$, ${}^{19}\text{Ne}$ isotope, used for β -decay measurements in Laser-traps
Western Michigan University (WMU) 6 MV Tandem	RBS, NRA, channeling, ion irradiation Development and testing of detectors for the low energy nuclear physics community

4.1.6 SUMMARY OF UNIQUE CAPABILITIES PROVIDED BY ARUNA FACILITIES

- Mono-energetic Gamma beam (TUNL)
- Mono-energetic Neutron beams (UK, OU, TUNL, UML, ND)
- Long-base line (30 m) neutron time-of-flight spectroscopy (OU)
- High-intensity light-ion beams for Nuclear Astrophysics (TUNL-LENA, ND-Caspar)
- High-Intensity heavy-Ion beams for Nuclear Astrophysics (ND-St.Ana)
- High-resolution magnetic spectrographs (FSU, TUNL-Tandem, ND-Tandem)
- The only high-resolution spectrometer at a Cyclotron facility in North America (TAMU)
- High-intensity activities of ${}^6\text{He}$, ${}^{19}\text{Ne}$ for precision measurements (UW)
- X-ray digital imager with 2-D and 3-D imaging capabilities (JMU)
- World's only triple-solenoid separator (ND-TriSol)

OTHER ACCELERATOR FACILITIES

The 88-Inch Cyclotron at LBNL is a unique asset to the US nuclear science and space effects community. It is supported in part by DOE-NP. The capability to produce intense heavy ion beams, and to devote exceptionally long run times to experiments enables world-class research to be pursued on the physical and chemical properties of the heaviest known elements. An exciting and credible opportunity is to use these capabilities to pursue a new element discovery, as is documented in a whitepaper to this Town Hall meeting. In addition, the 88-Inch Cyclotron supports an active and growing program of targeted measurements that address outstanding nuclear data needs, while training the next generation of scientists and engineers.

Nearly every U.S. space mission has had parts tested at a DOE-NP laboratory, including planetary and solar probes, space telescopes, and the Orion spacecraft that is expected to take humans back to the Moon and Mars. The first Single Event Effects (SEE) tests using heavy ions were conducted by the Aerospace Corporation as far back as in 1979. Since that time, radiation effects testing has continued at DOE-funded nuclear physics facilities (Berkeley Lab's 88-Inch Cyclotron, Brookhaven National Lab, TAMU, and Michigan State University) where heavy ions are used on Earth to mimic the cosmic ray damage that the electronic parts will experience in the increasingly important realm of the military and commercial space environment.

Additional relevant information can be found in the 2022 US Heavy Element Whitepaper, [The Status and Ambitions of the US Heavy Element Program](#).

THE CENTER FOR ACCELERATOR TARGET SCIENCE (CATS) AND OTHER TARGET MAKING FACILITIES

The Physics Division at Argonne National Laboratory (ANL) operates a target development laboratory in direct support of the experimental program at ATLAS and at other low-energy nuclear physics research facilities. This National Center for Accelerator Target Science (CATS) has been created based on the existing target development laboratory at ANL and, in collaboration with the previous Gas Jet/Advanced Targets Working Group, is the point of contact for the FRIB Users Target Working Group.

The objectives of the center are as follows:

1. Serve the DOE-NP low-energy community by producing targets whenever possible by either manufacturing them or by directing requests to other facilities best able to perform the task;
2. Train individual investigators and students in target making in order to provide a workforce capable to address present and future needs;
3. Carry out R&D activities dedicated to novel production techniques and optimization of existing ones;
4. Maintain an inventory of existing targets that serve as a pool available to the entire community.

The CATS infrastructure consists of five facilities within ANL's Physics Division: 1) The Target Fabrication Laboratory, where natural occurring and enriched stable isotopes in elemental or compound form are processed, 2) The Target Research and Development Laboratory which is dedicated to the development of novel accelerator targets, and to new target production methods, 3) The Radioactive Material Handling Laboratory (RMHL) which is becoming more and more important with the increasing demand for radioactive targets, 4) The Radioanalytical Counting Laboratory which is directly connected to the RMHL for immediate characterization of targets and sources, and 5) The Target Library and Archives where accumulated targets from ATLAS and targets from other institutions were recovered and inventoried, and are made available to the community. These facilities are continuously updated to maintain the state-of-the-art capabilities necessary to fulfill the needs of the community.

Following the Low Energy Community Meeting (LECM) in 2021 a survey was taken about future target needs of investigators conducting their research at ATLAS, NSCL/FRIB (with fast and reaccelerated beams), University laboratories and international facilities. It was found that the majority need thin targets of highly enriched isotopes with precisely known thickness. In addition, half of them also request radioactive targets. Additional user needs refer to thick targets for fast radioactive beams and isotope production, very thin charge-reset foils, gaseous, liquid or frozen targets and many plastic foils for e.g. (d,p) reactions. Upgrades to CATS are planned to ensure that these needs are met, particularly in the RMHL, where the expanded needs of the community for radioactive targets will require significantly increased capabilities. Failure to address this need in a timely manner would have a significant impact on scientific research in the US when necessary targets cannot be supplied for programmatic missions.

It should also be noted that additional, more limited target-making facilities are available at some of the ARUNA facilities. They are tailored mostly toward local research programs but are usually able to assist when CATS is overloaded. Furthermore, a new target laboratory is currently being developed at San Jose State University, a MSI & PUI institution. The primary mission of this laboratory, housed in the chemistry department, is initiating undergraduate students to fabrication techniques while at the same time introducing them to nuclear science.

COMMUNITY INSTRUMENTATION

The nuclear structure and nuclear astrophysics communities have a long history of design, development, installation, and operation of large-scale instruments built as collaborative efforts by members of these communities for the benefit of all. Five of these are discussed in some length below.

The flagship 4π Gamma-Ray Energy Tracking Array (GRETA) [GRETA14, GRETA20] will fulfill a core capability of high-efficiency γ -ray detection with high resolution in energy and position. GRETA is critical to realizing the physics opportunities at FRIB and ATLAS, with fast-fragmentation, re-accelerated and stable beams. The project is on track for Phase-1 deployment at ReA and the S800 beamline at FRIB in FY25, with completion in FY26. Currently 12 of 18 detector modules have been ordered (8 delivered), the mechanical systems are under procurement, and pre-production electronics are being tested. Since the 2015 LRP, additional detector modules have been added to the 1π tracking array GRETINA (totaling 13). GRETINA has been deployed for the first FRIB experiments using fast fragmentation beams delivered to the S800 spectrograph, and a modified GRETINA frame is planned to house up to 20 GRETA/GRETINA detector modules for future in-beam gamma-ray experiments at the S800 spectrograph until GRETA can be installed at the HRS.

Digital Gammasphere [DGS22] has been in operation at ATLAS since the 2015 LRP, providing substantial rate capability gains for high-resolution Compton-suppressed γ -ray spectroscopy experiments standalone, and with the FMA and the AGFA separators. A recent upgrade project is underway to replace aging front-end electronics. This upgrade also substantially reduces the footprint of the DAQ electronics, increasing the mobility of Gammasphere for deployment in other experimental areas, such as the low-energy hall for decay measurements with CARIBU beams.

The FRIB Decay Station (FDS) [FDS22] is a proposed suite of γ , neutron and charged-particle detectors for high-resolution and high-efficiency decay spectroscopy measurements at FRIB. This capability is critical for exploratory studies of the most exotic nuclei, and precision measurements of beta-decay properties, impacting all four strategic areas and benchmark programs [NSAC07, NSAC15]. FDS brings substantial improvements in resolution, efficiency, granularity, and rate capability - including 1-2 orders of magnitude in $\beta\gamma$ efficiency. Since the 2015 LRP, the FDS Initiator (FDSi) [FDSi22] has been assembled from existing community detectors, as a first step toward the FDS, and has been deployed successfully to enable the first FRIB experiments [Cra22]. The FDS was one of two new instruments identified as a high priority for construction in the resolutions from the 2022 Nuclear Structure, Reactions and Astrophysics Town Hall Meeting. A schematic view of the FDS is below.

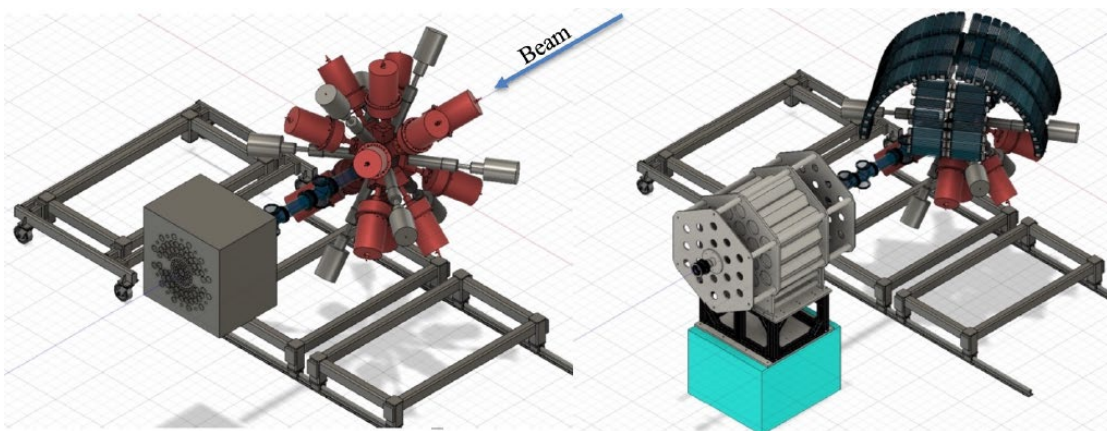


Figure 4.4: Conceptual design of the FDS.

The Oak Ridge-Rutgers University Barrel Array (ORRUBA) [ORR05] comprises the largest suite of silicon detectors for low-energy nuclear physics in the US, optimized for reaction experiments. ORRUBA operates at FRIB, ATLAS and ARUNA laboratories either in standalone mode, as the primary detector for the JENSA gas-jet target, or coupled to recoil separators (S800, FMA, SECAR). Since the 2015 LRP, the GODDESS coupling of ORRUBA to the large community arrays Gammasphere and GREINA has been developed and deployed for high-resolution measurements of formation and decay channels. Multiple upgrades are in progress, including compatibility with GRETA to provide a high-resolution 4π particle- γ spectrometer for FRIB.

The ReA9/12 accelerator at FRIB will provide world-unique, high-quality beams of reaccelerated fragmentation products, delivered at optimum energies and emittance to apply numerous well-characterized reaction techniques to study these rare isotopes (including scattering, transfer, Coulex and surrogate reactions), addressing the majority of FRIB's benchmark programs [NSAC07]. ISLA [ISLA15] is a proposed large-acceptance (64 msr, +/- 10% in momentum and charge state) recoil separator for ReA9/12, with high M/q resolving power (>1/1000). ISLA is crucial to realizing the physics potential of the reaccelerated beam program at FRIB, providing critical channel selection and beam suppression at full reaccelerated beam intensities for experiments with numerous community target and focal-plane detectors, including GRETA. ISLA was one of two new instruments identified as a priority in the resolutions from the 2022 Nuclear Structure, Reactions and Astrophysics Town Hall Meeting. A schematic figure of the device is shown below.

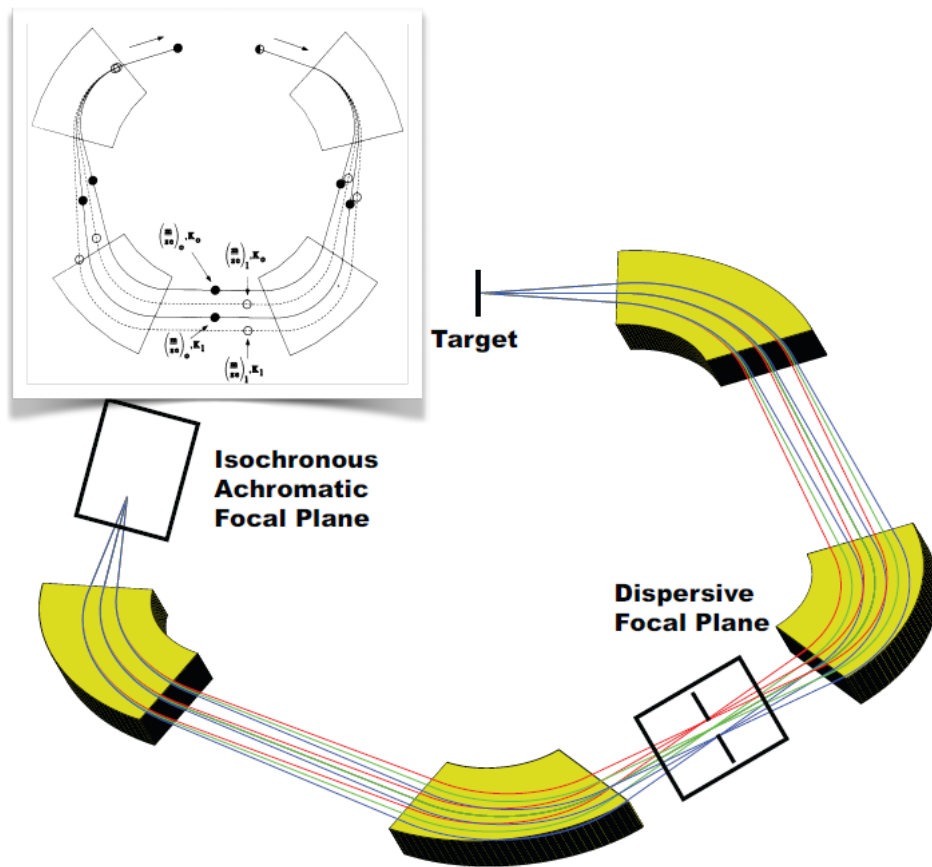


Figure 4.5: Conceptual design of the ISLA spectrometer.

OTHER DETECTORS AND FACILITIES

The science driving the field of low-energy nuclear physics requires a large number of experimental techniques. As a result, attention is constantly being paid to the development of new instrumentation to be used at the national user facilities (FRIB and ATLAS), at the ARUNA laboratories, or at both. New techniques are being actively pursued together with further developments of existing ones. A large fraction of the community is involved in these efforts where new, small-size, and large-scale instruments are being conceived, designed, and constructed. In many instances, these efforts provide invaluable hands-on experience to students (undergraduate and graduate) and postdocs, and herewith contribute significantly to the education of the nuclear science workforce of the future.

Many short contributions to this Town Hall meeting covered most of these initiatives. These are too numerous to be listed here and the reader is referred to the individual presentations on the meeting website.

The importance for the field of nuclear structure, reactions and astrophysics of laboratories supported by other government stake holders should not be overlooked as these institutions provide access to facilities and develop concepts of interest to this community. For example, LANSCE at Los Alamos National Laboratory (LANL) provides the world's brightest time-of-flight neutron facility for nuclear physics and is equipped with first-rate instrumentation. Furthermore, studies are underway at LANL for a proof-of-concept experiment at LANSCE in which a beam of gold ions will eventually interact with a thermalized neutron field generated by the interaction of the high-energy proton beam with a spallation target located inside a moderator. If successful, this initiative could lead in the long run to the development of a storage ring for long-lived radioisotopes where the interactions of exotic nuclei with neutrons could be investigated. Nuclear astrophysics studies for the s-, i- and r-processes would benefit from such developments.

More information can be found at <https://indico.phy.anl.gov/event/22/page/62-facilities-detectors-upgrades-working-group>.

CONCLUSION

At the present time, FRIB is carrying out first experiments with world-class equipment developed with large community involvement. At the same time, the ATLAS facility continues to serve a large number of users while upgrading its capabilities to meet demand. ARUNA facilities complement these two user facilities while often providing unique additional capabilities (types of beams, beam time, detectors). The community continues to upgrade its existing detectors while also developing first rate instrumentation and new concepts to further expand the reach of the science. However, as outlined above, to reach its full potential the field requires a number of modest investments. These all represent opportunities for development of the next generation of nuclear scientists for the benefit of society. With these provisions, the future is bright.

BIBLIOGRAPHY

[Cra22] H.L. Crawford *et al.*, Phys. Rev. Lett. 129, 212501 (2022).

[DGS22] L. Begley *et al.*, Nucl. Instr. and Meth. in Phys. Res. A 1040, 167113 (2022).

[FDS20] [FDS White Paper](#) (2020).

[FDSi20] [FDSi White Paper](#) (2020).

[FRIB400] [FRIB400 – The Scientific Case for the 400 MeV/u Energy Upgrade of FRIB](#).

[GRETA14] [GRETA White Paper](#) (2014).

[GRETA20] [GRETA Final Design Report](#) (2020).

[ISLA15] [ISLA White Paper](#) (2015).

[McG21] K. McGee *et al.*, Phys. Rev. ST Accel. Beams 24, 112003 (2021).

[NSAC07] [NSAC Rare Isotope Beam Task Force Report](#) (2007).

[ORR07] S.D. Pain *et al.*, Nucl. Instr. and Meth. in Phys. Res. B 261, 1122 (2007).

5 PREPARING A NUCLEAR WORKFORCE FOR THE BENEFIT OF SOCIETY

The number of people currently being trained and educated in nuclear science is insufficient to meet the workforce needs of academia and research laboratories—including national laboratories—industry, and other sectors. We must work as a community to attract highly qualified persons from all groups, including those now underrepresented in nuclear science. To fulfill our science mission and provide a highly qualified workforce for societal needs, we recommend beginning education in nuclear science at a young age, continuing through all stages of a student’s career, and reaching out to educate the public, including parents, politicians, and taxpayers.

The ability to attract, grow and sustain a national nuclear workforce depends on our community’s commitment to diversity, equity, and inclusion. It is essential that institutions and workplaces be supportive, diverse, and inclusive, naturally promoting inquisitiveness, intellectual curiosity, and engagement. We must be committed and vigilant in creating environments where all people can succeed and are, at the minimum, free from harassment. To increase diversity and retain talent, institutions should examine the salaries of graduate students, postdoctoral fellows, and all trainees to ensure they are keeping pace with inflation. Please see Sec. 6 on Creating a Welcoming and Inclusive Environment in Nuclear Science.

EDUCATING THE PUBLIC IN SCIENTIFIC LITERACY

The first step in recruitment or support for scientific research is to achieve understanding and “buy-in” from politicians, parents, and taxpayers. Not only should the public be aware of the need for nuclear scientists, but they should also know that federal tax dollars largely fund physics research in the United States. The nuclear physics community has a responsibility to provide Americans the opportunity to learn about the results of this research and how it may someday improve lives in our nation. Furthermore, it is in the best interest of the nuclear physics community to build a diversity of robust channels of information intended for the public to assist in maintaining public support for the nuclear research enterprise. In general, outreach is most effectively performed by individual institutions as part of their local communities. For example, FRIB has undertaken a number of local public activities including laboratory tours, science festivals, art shows, and local talks for a general audience.

The social media landscape has grown explosively since the last Long Range Plan, and has been distributed over many platforms. As a result, the efforts of many individual nuclear scientists will be required to provide content about current nuclear science research through each of these platforms and to reach a wide variety of audiences of different ages and backgrounds.

Some researchers are making use of social media and new technologies to attract younger participants or the public. *Quantum 3* is an educational game played on a model device developed by Huey-Wen Lin at Michigan State and teaches kids about quantum properties. *My Nuclear Life* is a podcast created by Shelly Leshner at the University of Wisconsin, La Crosse, and discusses the intersection of nuclear science and society to inform the public. One measure of impact is its download numbers which place it in the top 10% of all podcasts.

Fortunately, many nuclear physicists seem interested in participating in the effort to provide this vast array of content. However, few nuclear physicists have job descriptions that allow them to count activities producing content on nuclear science for the public in their annual evaluations. Producing such content for the public requires considerable effort, and the hours that a scientist spends doing this work likely reduce the volume of research or service that they can produce in a year and that count directly toward the researcher’s annual evaluation. Therefore, the nuclear physics community should resolve to support its members in their work to inform the public about nuclear science. Researchers at both universities and national laboratories should have opportunities to have the

production of high-quality content for public consumption included in their job descriptions and their annual evaluations, as recommended by the APS Committee on Informing the Public [SMI21].

INTRODUCING PRE-COLLEGE STUDENTS TO NUCLEAR SCIENCE

Students begin making decisions about careers and preparing for those careers long before they begin college. Middle school is a key educational stage for students who are members of groups underrepresented in math-intensive STEM fields like physics. For example, although girls and boys have similar math performance in their K-12 education, girls lose interest in STEM much earlier than boys do. Effective strategies to keep them engaged include active learning exercises to teach material and communicating the societal impact of STEM. Such strategies make these fields more attractive to everyone but especially to girls, boys who are members of underrepresented groups, and first-generation college students [NA2020].

The one-week Nuclear Medicine and Science Summer Camps for middle school students held at both Florida State University (FSU) and Texas A&M University (TAMU) provide an example of an engaging activity that might prompt a young person to consider a career in nuclear science. These camps are free to families and are led by community teachers who engage in hands-on activities using radiation monitors and gamma-ray spectrometers. The involvement of these teachers from the community is important because the most effective informal STEM educational experiences involve buy-in from individuals who play important roles in students' lives, such as parents and teachers [DES16]. Faculty from the two laboratories provide training and on-site assistance to these 'lead teachers', one of whom is pictured in Figure 5.1 with a student. The societal impact is communicated through lectures and visits to local nuclear medicine facilities. Online resources like the gamma-ray coincidence experiment mounted by Washington University in St. Louis provide additional future resources for these camps.



Figure 5.1: Denise Newsome was a physics/chemistry/calculus teacher at Deane Bozeman School, a rural school about 20 miles north of Panama City when she joined efforts with Paul Cottle for the FSU Nuclear Medicine & Science Camp in summer 2020. She is now Director of Youth Initiatives for the ASCENT Program at FSU's Panama City Campus and continues to be an integral part of this effort.

Other laboratories also host summer activities for pre-college students. The Physics of Atomic Nuclei (PAN) residential summer program for high school students has recently been supported by JINA-CEE at Michigan State University and the University of Notre Dame and will continue in 2023 at Michigan State with support from FRIB. PAN has competitive admission and attracts applicants from a wide geographic region.

These programs educating pre-college students are important whether the students go into nuclear science careers or not. Students who have learned about nuclear science and the good it can do in society will be more informed

citizens. And the math skills and scientific reasoning introduced in the programs will also transfer to other STEM fields.

HIGHER EDUCATION

PhD trained nuclear scientists are highly sought after for employment in academia and fundamental research, national laboratories, (for-profit) corporations, governmental organizations, and federally funded research and development centers. With the increasing demand for a workforce versatile in data science and other skills acquired by students in nuclear science, an increasing number (now at 50%) of PhD graduates are recruited by for-profit and non-profit corporations, compared to 35% who find employment in academia, and 14% in governmental organizations [AA21]. The number of PhD graduates in nuclear science has increased from about 80 per year prior to 2014 to around 100 per year since then (see Figure 5.2), but it has not been sufficient to make up for the increased workforce demands. For example, it has become very difficult to recruit postdoctoral researchers in nuclear science, particularly those who are U.S. Citizens and who are critical for supporting national needs in security, non-proliferation, and defense sectors.

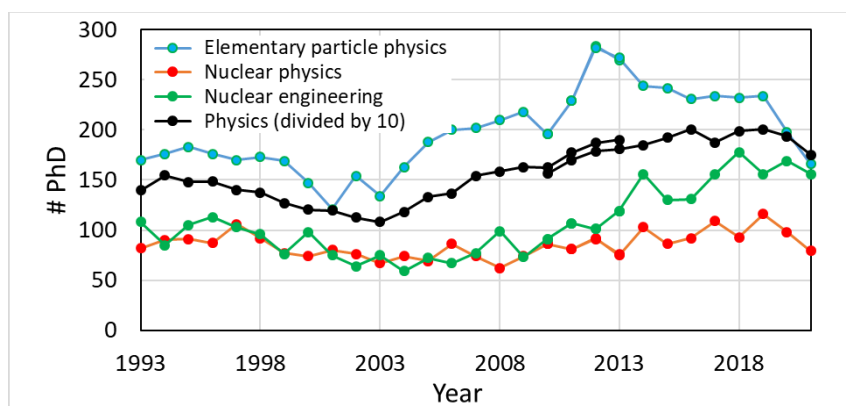


Figure 5.2: Number of PhD graduates per year since 1990 for physics and subfields of nuclear physics, particle physics, and nuclear engineering [SED22]. Drops in graduation rates in 2020 and 2021 could be related to the impacts of the global pandemic, but the aftershocks of this event are not yet known.

The field's ability to train the next generation of PhD nuclear scientists depends on funding levels to support graduate students and mechanisms to recruit and retain students in graduate programs. To attract graduate students, it is important to explain to students at all levels that skills acquired while pursuing a PhD in nuclear science provide access to a very wide range of rewarding career paths in and outside of academia and fundamental research. This includes communication to students about societal impacts of physics, an area shown to increase interest of students who have been underrepresented in physics [NA2020, TEAMUP]. The impact of nuclear physics is very clearly felt at the national laboratories which can provide stable careers for scientists. Demonstrating this impact is also very important for reaching out to students who might otherwise never consider pursuing a career in nuclear science and to increase the number of PhD-trained nuclear scientists that are from groups presently underrepresented in the field. Figure 5.3 shows how low the percentages of underrepresented minorities are in physics. If these students' interest in nuclear physics can be encouraged, they can bring the diversity of background that the nuclear science community needs to be successful in the long term. The number of women graduates in nuclear science has remained at around 20% since 2009, a percentage similar to physics overall. Similarly, the number of graduates from underrepresented racial and ethnic groups in the U.S.¹ has remained low (~10%) compared to national demographics (~33%) since 2012 and the percentage of graduates who are White and not Hispanic or Latino remain

overrepresented (~75%) compared to national demographics (59% [CEN20]). This is very similar to the trends observed in physics graduate programs overall. The percentage of graduates in nuclear science who are temporary visa holders has remained at 35%, slightly below the percentage in physics (~42%), possibly reflecting the desire to recruit persons whose potential career paths might require U.S. citizenship.

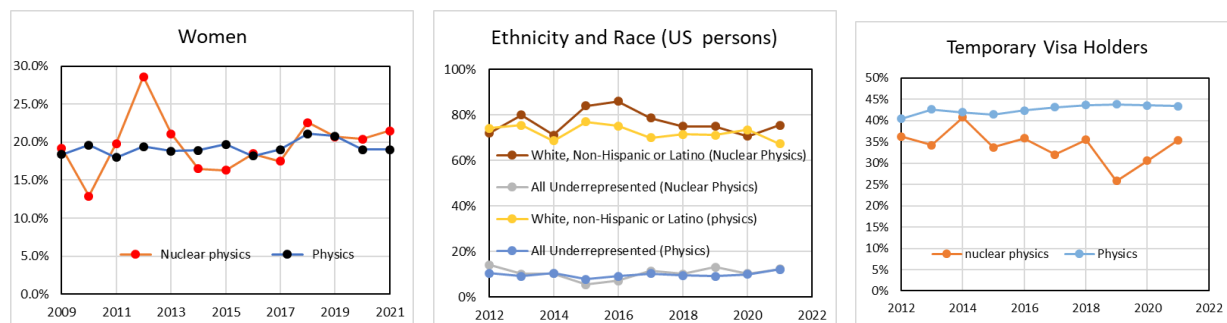


Figure 5.3: (Left) Percentage of PhD graduates who are women in physics and nuclear physics since 2009; (Middle) Percentages of graduates (US Citizens or Permanent Residents) in physics and nuclear physics who are from underrepresented groups¹ and who are white; (Right) Percentage of PhD graduates who are temporary visa holders in physics and nuclear physics. Data are from Ref. [SED22].

There are a wide variety of important activities in low-energy nuclear science aimed at providing gateways into (nuclear science) graduate programs, and which also aim to enhance the participation of students who are in underrepresented groups, including efforts that have started recently. NSF—through the Research Experience for Undergraduates (REU) program—and DOE—through the Science Undergraduate Laboratory Internships (SULI) program—support the early participation of undergraduates in research and are critical for making students aware of opportunities through graduate education. This is particularly important for students who have no opportunity to carry out nuclear science research at their own institutions, such as primarily undergraduate institutions (PUI) that play an important role in providing well-rounded education to undergraduate students. The NSF funded Nuclear Science Summer School (NS³) provides an opportunity for these students to get acquainted with the field of nuclear (astro)physics. Similarly, the DOE funded American Chemical Society (ACS) Nuclear Chemistry & Radiochemistry summer school introduces undergraduates to the fundamentals of nuclear science, radiochemistry, and their applications in related fields.. Collaborations between PUIs, universities, and laboratories that have advanced research facilities are also very helpful to engage a larger group of students in nuclear science research, often leading to published research, see e.g. [RAM22, LES22] for recent examples.

Other excellent avenues to prepare students for graduate research in nuclear science and reduce the loss of talented students between BS and PhD is through Master’s programs in which students are exposed to nuclear science research, such as the program offered at Central Michigan University. Other examples are post-baccalaureate programs offered by many national laboratories, which also allow students to develop relevant skills while gaining confidence in their abilities to pursue a PhD degree and to see up close the career opportunities afforded to PhD scientists. These are important possibilities for students from first-generation families and those who are unsure they want to make a commitment to a PhD program.

¹ Defined by NSF as U.S. persons who are “Blacks or African Americans, Hispanics or Latinos, and American Indians or Alaska Natives”

The university-based research facilities organized in the Association for Research at University Nuclear Accelerators (ARUNA) play critical roles in preparing highly qualified students for the workforce in nuclear science. Students have the opportunity to engage on a daily basis with state-of-the-art nuclear science research and facilities and help develop new techniques that also find use at larger research laboratories such as FRIB and the National Laboratories. The Center for Excellence in Nuclear Training and University Based Research (CENTAUR), supported by DOE-NNSA, and the Horizon-broadening Isotope Production Pipeline Opportunities (HIPPO), supported by the DOE Isotope program, provide strong partnership in support of training junior researchers in nuclear science.

As part of the Reaching a New Energy Sciences Workforce (RENEW) initiative by the DOE Office of Science, several traineeship programs have emerged that support long-term training, mentorship, and research experiences at universities, colleges, DOE user facilities, and DOE national laboratories for undergraduates from minority serving institutions. Seventeen traineeship programs involving a wide range of minority serving institutions with connections to various universities and laboratories in low-energy nuclear science were recently established by the DOE. The 'Institute for Nuclear Science to Inspire the next Generation of a Highly Trained workforce,' or INSIGHT Center, has the charge to measure progress and coordinate longitudinal tracking of trainees' progression towards science and technology careers. The Student Training and Engagement Program for Undergraduates in Physics (STEP UP – a collaboration between JLAB and FRIB) and Physicists Inspiring the Next Generation (PING) programs provide additional ways for guiding students from minority-serving institutions towards a career in (nuclear) science.

At the graduate level, the DOE Science Graduate Student Research (SCGSR) Program has, since 2014, provided valuable opportunities for PhD candidates in fields across the programs supported by the DOE, including in low-energy nuclear science, to spend several months in residence at a DOE laboratory collaborating on their thesis research. This program both enhances graduate training and helps address workforce shortages at DOE laboratories.

All the above-mentioned programs contribute to the Conference Experience for Undergraduates (CEU) program, which provides a capstone conference experience for undergraduate students who have conducted research in nuclear science by providing them the opportunity to present their research, explore the field of nuclear science research (including a graduate school fair), and meet the community. In the last 10 years, over 72% of the students who participated in the CEU program have been tracked and 59% of them either have earned their PhD or are currently in graduate school. Most of those students, almost 90%, have studied or are studying physics, showing once again the impact undergraduate research has on advancing student interest in physics and pursuing advanced education.

It will take a few years to see the impact of some of these new initiatives on the ability to increase participation, but the need to train more graduate students and to increase the diversity of the applicant pool is urgent. Consequently, further steps are needed. Two types of activities can be undertaken. The first are community-wide initiatives (similar to the CEU program) in support of workforce development and education. For example, the wider variety of institutions students come from prior to entering graduate programs results in a wider variety of strengths and gaps in the students' academic background. The American Physical Society (APS) Bridge Program and strategies pursued at individual institutions aim to close these gaps. More broadly, there is an opportunity to work together as a nuclear science community to help students close these gaps through training, e.g. through summer-long programs aimed at academic preparation with components focused on nuclear science. Secondly, there are many activities at individual institutions that are impactful in enhancing student's education and career development, while improving diversity, equity, inclusion, and belonging. Such activities pertain, for example, to inclusive recruiting practices through the use of holistic review strategies, the creation of strong (peer-) mentoring networks, training in research based undergraduate and graduate mentoring practices, core-course support and restructuring of curricula to better

support students with very different backgrounds, program components that focus on the development of soft skills, better wellness and mental-health support, socio-economic support structures, and comprehensive career services. These practices are recommended to recruit and retain a diverse population into physics [NA2020, TEAMUP]. The development of these activities is important, but also takes time and resources. The nuclear science community, through workshops and sessions at APS Division of Nuclear Physics (DNP) meetings, can strongly support the sharing of best practices and activities, so that different programs and institutions do not have to duplicate efforts and can learn from each other's experiences.

POSTDOCTORAL RESEARCHERS

Currently, about half of new Physics PhDs accept positions as postdoctoral researchers [AIP]. These positions are short, typically one to three years but are usually an essential qualification for a permanent position in academia and National Laboratories. Thus, postdoctoral appointments must position early-career researchers to be competitive candidates for permanent positions. Successful postdoctoral researchers demonstrate that they can take intellectual leadership of projects, complete them, and share results through publications and oral presentations. The institutions who sponsor postdoctoral researchers and mentors and supervisors are responsible for creating an environment in which they can be successful. This environment should also be supportive to encourage the postdoctoral researcher to develop as a scientist by rewarding curiosity and acknowledging that mistakes can be a part of learning. All parties involved including the sponsoring organization and the funding agencies have roles to play in building this environment.

Institutions that sponsor postdoctoral researchers should establish internal structures to monitor their progress and provide helpful intervention when necessary. Some best practices for management include implementing 'skip-level reporting', in which the postdoctoral researcher has periodic meetings with their supervisor's supervisor. Institutions should encourage structures that enable postdoctoral researchers to meet and learn from their peers, provide resources for career development, such as workshops for writing papers and grants, and opportunities for postdoctoral researchers to present their work internally. Sponsoring organizations should make research-based mentor training available to advisors (as recommended by the National Academies [MEN2019]) and equip them with effective management tools. These structures will not only improve the competitiveness of the postdoctoral researcher for their next position, but they will increase the attractiveness of the institution to prospective postdoctoral researchers.

Mentors bear most of the responsibility for ensuring that the postdoctoral researcher can work in an environment conducive to success. Mentors are responsible for continuing the education of the postdoctoral researcher. They should encourage intellectual growth, both by enabling postdoctoral researchers to follow and develop their own interests, and by recognizing that gaps in knowledge are opportunities for education. Mentors should ensure that the postdoctoral researchers with whom they work can maintain a healthy work-life balance and have the support and resources they need to discharge their responsibilities. Mentors should take responsibility for equipping postdoctoral researchers to compete for their next position, which can include assistance with writing first-author publications and advocating for the researcher to present their work in high-profile venues.

Everyone involved should recognize that, while a postdoctoral position can be exciting and rewarding, it may also require significant sacrifice on the part of the researcher. The postdoctoral researcher may incur opportunity costs: both monetary (salaries for postdoctoral researchers are typically about 30-50% lower than permanent private sector positions [AIP]) and personal (postdoctoral researchers are usually young people and are often required to relocate which can place significant stress on relationships). An environment that recognizes the challenges, personal

and professional, that postdoctoral researchers face and enables them to meet them will create a diverse and intellectually nimble workforce that will lead our field forward to an exciting future.

NEW DIRECTIONS IN GRADUATE AND POSTDOCTORAL EDUCATION AND TRAINING

The 2015 LRP emphasized the importance of new directions in the education and training of graduate students and postdoctoral scholars, beyond the resources available at individual educational institutions. No one institution can offer cutting-edge instruction on all foundational and frontier topics within the field with high frequency, and most are challenged to offer even a basic complement of graduate classes. Students and junior researchers in smaller groups are at best exposed to "only a part of the full spectrum of ideas and styles of doing nuclear physics" [LRP15, p. 108].

A set of initiatives to address these educational needs had emerged within the field at the time of the last LRP. These initiatives have now matured, and form an essential component of advanced education within the field:

- The National Nuclear Physics Summer School (NNPSS) provides a general overview of nuclear physics, while "facilitating interactions among experimental and theoretical students in all subfields of nuclear science".
- The Exotic Beam Summer School (EBSS) provides a mix of lectures and hands-on activities for students and postdocs interested in opportunities with rare isotope beams.
- The Training in Advanced Low Energy Nuclear Theory (TALENT) initiative has the mission of developing a broad curriculum of summer school courses, providing cutting-edge theory for understanding nuclei, their reactions, and astrophysics, serving both theoretical and experimental students.
- More recently, the FRIB Theory Alliance (FRIB-TA) established a series of summer schools on theory relevant to FRIB physics.
- To address the need for university course materials at a more introductory level, prototype nuclear physics survey courses were developed and disseminated under the auspices of the FRIB-TA Education Committee. These courses cover all areas of contemporary nuclear physics, from QCD to nuclear astrophysics, with the learning goal that students can understand and explain the physics featured in the National Research Council report, *Nuclear Physics: Exploring the Heart of Matter*, and the 2015 NSAC Long Range Plan, *Reaching for the Horizon*.

Continued support is needed to keep these efforts vibrant, while a goal going forward should be to expand both their scope and their reach within the nuclear physics community. New modes of instruction of communication make this possible.

For example, the TALENT initiative has developed a repertoire of three-week intensive summer courses (eleven to date), integrating extensive practical exercises and computational projects. Several of these courses (in nuclear structure, machine learning, nuclear reactions, nuclear forces, and nuclear astrophysics) have now been offered more than once and have matured to the point that they could be offered as online learning material with videos, exercises, and projects. The resulting "repository of consistent and well-linked teaching materials" [LRP15, p. 110] would then be available on demand to a broad spectrum of potential beneficiaries.

The goal of providing a robust set of graduate courses to students across the nuclear science community would be addressed by further initiatives to develop shared course materials at all levels. More broadly, such initiatives could aid in making a wide range nuclear science courses available to undergraduates as well. Simply developing and disseminating comprehensive model course materials, exploiting effective pedagogical practices such as active learning would already reduce the barrier for small programs to offer courses. The recent explosion in familiarity

with hybrid and remote learning formats opens the door to new possibilities for sharing limited teaching resources among institutions. In one model, a single host institution provides a hybrid class, both to its own local students and individual remote participants from various other institutions (whose advisors sign off on credit at the remote institution). In another model, the instructor at the host institution still takes responsibility for providing hybrid lectures and the core course materials, while instructors at partner institutions provide tutorials and grading for their own students. For such efforts to be efficient and sustainable, it would be incumbent upon the nuclear science community to provide some coordinating structure and administrative support (whether through an existing organization or some dedicated new 'nuclear physics year-round school'). Such formal recognition would aid in institutional buy-in, both by lead institutions (which incur an additional teaching burden in supporting remote students) and remote institutions (to recognize the courses for credit).

CONCLUSION

It is important for the health of the nuclear science community and our service to the nation to educate young people and the public in nuclear science. The number of people being educated in nuclear science needs to grow to keep up with national needs. There are several independent dynamic programs working on this important endeavor at institutions across the country. This is important because individual institutions and communities are unique in resources and needs. The town hall offered an opportunity for many of these programs to share ideas for the first time. It is important that the community shares information and best practices in support of education, work force development, and public engagement. This could potentially lead to community-wide initiatives, such as the CEU program.

BIBLIOGRAPHY

[SMI21] M. Smith *et al.*, Informal Science Education and Career Advancement, A White Paper by the APS Committee to Inform the Public. Doi.org/10.48550/arXiv.2112.10623 [<https://arxiv.org/abs/2112.10623>]

[NA2020] National Academies of Sciences, Engineering, and Medicine 2020. Promising Practices for Addressing the Underrepresentation of Women in Science, Engineering, and Medicine: Opening Doors. Washington, DC: The National Academies Press. [<https://doi.org/10.17226/25585>]

[DES16] Designing for Success. Positive factors that support success in STEM pathways and reduce barriers to participation: what does the research say about what enables students to succeed and persist in STEM fields? (2016). The Institute for Broadening Participation. [www.pathwaystoscience.org]

[TEAMUP] The AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) 2020. The Time is Now. Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy. College Park, MD: American Institute of Physics. [www.aip.org/teamup]

[MENT2019] National Academies of Sciences, Engineering, and Medicine 2019. The Science of Effective Mentorship in STEMM. Washington, DC: The National Academies Press. [<https://doi.org/10.17226/25568>.]

[AA21] Data from Academics Analytics for the Michigan State University Graduate Program (2021).

[SED22] National Science Foundation Survey of Earned Doctorates. [<https://www.nsf.gov/statistics/srvydoctorates/>]

[CEN20] United States Census Bureau 2020. [<https://www.census.gov/quickfacts/fact/table/US/POP010220>]

[LES22] S.R. Leshner *et al.*, Phys. Rev. C 106, 044302 (2022).

[RAM22] A.P.D. Ramirez *et al.*, Nucl. Phys. A 1023, 122446, (2022).

[AIP] Initial Employment: Physics Bachelors and PhDs. Classes of 2019 and 2020.

[<https://www.aip.org/sites/default/files/statistics/employment/empbooklet19and20-latest.pdf>]

[CAP] Salary Cap, Stipends, & Training Funds. [<https://www.niaid.nih.gov/grants-contracts/salary-cap-stipends>]

6 CREATING A WELCOMING AND INCLUSIVE ENVIRONMENT IN NUCLEAR SCIENCE

INTRODUCTION

The American Physical Society's Ethics Guidelines 19.1 states that "[t]he American Physical Society values a diverse membership and supports the right of all people to pursue the study of physics and to participate in the physics community free from discrimination." It goes on to state "research has shown it is not unusual for members of groups defined by sex, race, and color to feel unwelcome in physics" and "[m]ore members of groups that have historically been excluded or discouraged from physics would bring valuable contributions to the field if barriers to their participation were removed" [APS2022]. To do the best nuclear science, we need to grow and cultivate a more diverse community in which everyone feels welcome, and where each of us treats all others with dignity and respect.

Every individual, including importantly those in leadership, have a responsibility to contribute time and effort to the promotion and advancement of Diversity, Equity, Inclusion, and Belonging (DEIB) in our community. We are striving to become a more diverse community in which every individual feels welcome, valued, and treated with dignity and respect. The present reality is that we are not nearly as diverse as we need to be, and that far too many individuals experience harassment and bullying from our own community members, leading to a sense of being outside the community and unwelcome. As long as individuals can harass others without consequence, any gains in becoming more diverse are lost when people leave as a result of the negative treatment and lack of support they receive, a net loss for our community. Therefore, we must engage in serious efforts to "promote and sustain a diverse, equitable, and inclusive nuclear science workforce [that] will be fully integrated into every aspect" of our work [NSAC2022].

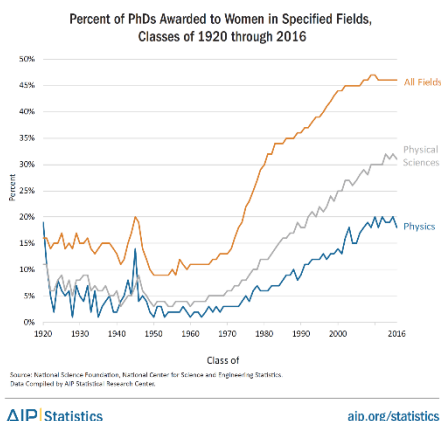
Several positive DEI-related initiatives and programs in nuclear science have emerged in recent years as part of a communal effort to increase diversity in nuclear science and encourage and support participation of those from underrepresented groups through outreach, recruitment, and retention. Several examples of such initiatives are highlighted later in this report.

This section reports on: Current Diversity in Nuclear Science; Experiences of Underrepresented and Marginalized Groups in Nuclear Science; LGBTQ+ Experience in Nuclear Science; Financial Stress on Graduate Students and Postdocs; Outreach Initiatives to Strengthen and Diversify Nuclear Science; DEIB Initiatives in Nuclear Science; and, Harassment in Nuclear Science. Specific recommendations appear at the end of each subsection.

CURRENT DIVERSITY IN NUCLEAR SCIENCE

The addition of a focus on increasing Diversity, Equity, Inclusion and Belonging (DEIB) for nuclear physics included in the Long Range Plan (LRP) signifies the urgency we face in tackling the issue of representation in physics. Physics stands out as one field where women and other minority groups do not represent the world we live in and more importantly does not mirror other fields in STEM. The lack of diversity among physicists is an ongoing problem and, while it persists, physics will fail to achieve its full potential. Supporting people from more diverse backgrounds in the physics community and making it truly representative of society is not only a matter of social justice and fairness, but will also increase productivity and potential for new discoveries. The following statistics from the American Institute of Physics (AIP) Statistical Research Center (<https://www.aip.org/statistics/reports/> [AIP2019, AIP2021]) highlight the current situation:

1. Women earn fewer than 20% of PhDs in Physics, with about 21% masters and 23% Bachelor's degrees going to women. (Year 2020). For comparison, the percentage of women obtaining PhDs in all fields is closer to 50% (see Figure 6.1, left).
2. The demographic that has experienced the smallest gain in representation in recent years is the African American group. From 2005 to 2015, the number of African American Bachelors recipients in all academic fields has increased by 43%. During the same time period, however, the number of African Americans earning degrees in physics has increased by only 4%, compared with an overall increase of 57% for all physics Bachelor's recipients [AIP2019a]. Both African Americans and women have experienced much bigger representation gains in fields other than physics.
3. For the classes of 2018 and 2019, African American represented only 1% of the Physics PhD degrees, while Asian American represented 9% and Hispanic American 4% (See Figure 6.1, right). The representation of Asian American and Hispanic American has shown a steady rise.
4. One positive sign is that the number of women in faculty positions and new hires has increased over the years.



Race and Ethnicity of Physics PhDs, Classes of 2018 and 2019 Combined.

	Number (2-Year Average)	Percent of all Physics PhDs	Percent of US Physics PhDs*
White	860	45%	84%
Asian American	92	5%	9%
Hispanic American	42	2%	4%
African American	9	<1%	1%
Other US Citizens	20	1%	2%
Non-US Citizens	887	47%	-
Total	1,910	100%	100%

*Based on a 2-year average of 1,022 US Citizens.

AIP Statistics

aip.org/statistics

Figure 6.1: (Left) Percent of PhDs awarded to women in physics, physical science, and all fields combined. (Right) Physics PhDs broken down by race and ethnicity from 2018-2019.

It is abundantly clear that physics has failed to attract and retain minorities. We need to reevaluate the culture we present to younger students and make the environment and culture work for everyone in the same way it works for the majority. Sexual harassment and gender and ethnic discrimination continue to persist in our field, driving good talent away, and must be addressed aggressively with concrete steps for holding perpetrators accountable.

We believe that our field is based on meritocracy, that is those with abilities and talents can excel. However, meritocracy often reinforces the clout of those who are already established, squashing the chances of lesser-known individuals to advance [Bar2022a]. There should be more openness in hiring, promotions, awards, invited talks etc.

Hopefully this white paper will be a call to action for all physicists to realize that there is a problem in our field, and work together both at the individual and collective level to advance DEIB. Those in privileged positions sometimes fail to realize small barriers can eventually in time become unsurmountable; "molehills" can turn into mountains!

EXPERIENCES OF UNDERREPRESENTED AND MARGINALIZED GROUPS IN NUCLEAR SCIENCE

Nuclear Physicists who identify as part of marginalized and underrepresented groups which include women, people of color, ethnic minorities, members of the LGBTQ+ community, individuals with a disability, and/or people with more than one of these identities, are disadvantaged in a multitude of ways. These groups have experienced a variety of workplace harassment and social exclusion as well as slower career growth opportunities compared with heterosexual, able-bodied, white men. For these marginalized groups, the workplace is often a different and more hostile environment than the one enjoyed by their white male counterparts. They are often paid less and are accorded less professional respect. Marginalization, discrimination, and harassment are seen as more frequent, while personal identities are perceived as more of an impediment than an advantage to the community.

Although the case of women in nuclear physics has improved somewhat over the past few years, with the group seeing an increase in leadership positions in the community and new faculty hires, gender discrimination and sexual harassment, as alluded to elsewhere in this section, remain major concerns for the community, causing many to leave the field. In the same fashion, a significant fraction of LGBTQ+ nuclear physicists have reported experiencing or observing discrimination, isolation, marginalization, and exclusionary behavior. According to a recent climate survey performed by the APS [Ath2016], about 31% of LGBT physicists have experienced harassment in their workplaces. This compares to about 44% of LGBT women who reported the same. The number is even higher (greater than 67%) in transgender and gender non-confirming physicists. This has resulted in about 36% considering leaving the community. Overall, the climate experienced by LGBTQ+ physicists in the workplace has remained highly variable, with those with additional marginalized identities facing even greater levels of discrimination. It is, thus, important that the community takes concrete steps to address the challenges facing LGBTQ+ physicists since they represent an invisible minority that intersects with many other underrepresented and marginalized groups.

African Americans and other racial and ethnic minorities are significantly underrepresented in nuclear physics (and physics in general), compared to their representation in the other STEM fields in the United States. In many ways, this underrepresentation has been associated with limited access to quality education at the foundational level (K-12 grades), discrimination in recruitment and promotion and a general lack of encouragement to pursue careers in physics from an early age. While there are no documented statistics or surveys regarding the experience of ethnic and racial minorities in the nuclear science community, there have been several reported instances of racial discrimination, with many, especially women of color, believing that their race or ethnicity has made it harder for them to succeed. Others have expressed concerns about hiring decisions, opportunities for promotion and pay equity, as well as persistence of strongly held stereotypical and preconceived notions about capabilities among colleagues. Thus, while there is no one policy initiative capable of solving the mirage of systemic issues experienced by underrepresented and marginalized groups, it is, nevertheless, imperative for the nuclear science community to begin to take concrete steps in building a framework that will promote and support the protection and participation of these groups.

It is also important to note that, while many DEIB efforts have concentrated on increasing the population of underrepresented and minority groups and reducing harassment and micro aggressions in nuclear science, far less attention has been paid to ensuring their long-term retention. The lack of work-life balance typically ranks very highly among the many reasons why members of underrepresented groups choose to leave STEM [Bru2019]. Within the research community, increased pressures from administrative and service tasks can lead to work-life balance difficulties and ultimately issues with retention. The 'service problem' is a name for the difficulty that individuals from underrepresented groups face when committee and panel membership at an institutional or community-wide

level is required to be diverse, but the diversity of the population from which the membership is drawn is not sufficient. When such a situation exists, members of underrepresented groups statistically will be required to do more service than their well-represented peers. Because service work, such as committees, mentorship, etc., require time and effort that would otherwise be spent on research, the service problem can cause increased negative impacts to the careers of individuals from underrepresented groups by detracting from their research output, hence lowering the likelihood of future promotion, tenure, award, or funding success. If members of underrepresented groups are subject to additional workload and increased barriers to promotion and funding, they will be more likely to leave the field. Overcoming the service problem is, hence, one step towards improving retention of underrepresented groups in STEM.

RECOMMENDATIONS

- Ensure transparency and equity in recruitment and hiring.
- Ensure a safe and welcoming environment at community meetings.
- Address the need to systematically accommodate name changes in publication records.
- Develop advocacy efforts that support LGBTQ+ equity and inclusion.
- Promote LGBTQ+-inclusive practices in academia, national labs, and industry.
- Implement LGBTQ+-inclusive mentoring programs
- Support the establishment of a Forum on Diversity and Inclusion.
- Expand committee membership to new candidate pools, to reduce the load.
- Develop a national database so that people can search for potential candidates to invite for committee/panel membership.
- Task promotion, tenure, funding, and award selection committees with addressing how someone's service burden might have detracted from their scientific output.
- Compensate people fairly for their service.

LGBTQ+ EXPERIENCE IN NUCLEAR SCIENCE

Understanding the statistics of LGBTQ+ representation is difficult due to the persistence of 'closet culture' within society. Due to consistent fear of retaliation, this culture is still present today though recent governmental and societal changes have begun to open the door for the LGBTQ+ community. In 2021, the Human Rights Campaign Foundation published that at least 20 million adults (nearly 8%) of adults in the U.S. identify as LGBTQ+ [HRC2021]. Assuming population statistics are consistent within nuclear physics, this is a significant portion of the community. Unfortunately, this portion is also more likely to have experienced discrimination and consider leaving the field of nuclear physics [Ath2016]. Therefore, concerted efforts are needed to foster a welcoming and inclusive environment. Throughout this section, a variety of specific issues pertaining to the LGBTQ+ community will be addressed along with recommendations.

Below is a brief listing of issues facing the LGBTQ+ Community:

- Sexual harassment, sexual assault.
- Discrimination, stigmatization, misunderstanding.
- Insulting, demeaning, disrespectful, discriminatory language is still acceptable under the guise of (i) freedom of speech, (ii) freedom of worship.
- Lack of visibility with an inability to comment on personal life (closet culture).
- Lack of representation in social, sports and recreational events.

- In large organizations, lack of information addressing the specific needs of LGBTQ+ individuals.
- Professional isolation: lack of networking opportunities with colleagues and peers which results in a stunted career growth.
- Lack of comprehensive health care benefits, including specific needs of transgender individuals.
- Lack of accommodations for non-binary, gender non-conforming, transgender individuals including single-stall restrooms or non-gender restrooms.
- Struggle to lead a fulfilling life in small cities and towns due to the lack of LGBTQ+ friendly organizations, encompassing basic needs such as (i) health care providers; (ii) childcare centers and schools; (iii) lawyers, accountants, financial advisors, and contractors; as well as organizations related to personal and social activities such as (i) places of worship, (ii) retail centers, hotels, restaurants, sports, and recreation.

To further understand the problems facing the LGBTQ+ community in physics, the American Physical Society Ad-Hoc Committee on LGBT Issues was charged in 2015 with assessing the barriers to inclusion in our community. They performed a detailed climate survey and summarized the findings in their LGBT Climate in Physics Report [Ath2016]. Unfortunately, a large fraction of physicists (>30% for LGBT men, >40% for LGBT women, and >65% gender non-conforming) had observed or experienced harassment in their departments and workplaces [Ath2016]. This harassment leads to common feelings of isolation and hostile environments that lead to LGBTQ+ physicists being at risk for leaving the field; 33% of survey respondents indicated they had contemplated leaving the field within the past year [Ath2016]. The committee also made several recommendations to improve conditions for LGBTQ+ physicists:

- Ensure a safe and welcoming environment at APS meetings.
- Address the need to systematically accommodate name changes in publication records.
- Develop advocacy efforts that support LGBTQ+ equity and inclusion.
- Promote LGBTQ+-inclusive practices in academia, national labs, and industry.
- Implement LGBTQ+-inclusive mentoring programs
- Support the establishment of a Forum on Diversity and Inclusion.

The APS has already begun tackling some of these recommendations. Meetings and conferences require a code of conduct to be followed and advocates trained in harassment response are made known. Many of these recommendations have also started to take root across academia and national labs. The development of advocacy/employee resource groups within institutions have begun making strides in providing support for the LGBTQ+ community. As isolation is one of the most common feelings, these groups provide community and belonging to staff and students who are part of the LGBTQ+ community and their allies. National laboratory employees cited the importance of employee resource groups with an emphasis on management/upper leadership support for their work. Not only do these groups provide space for the community they serve, but they also provide education to the broader community to create a better overall environment for the people they serve.

As societal and legal changes contribute to the overall acceptance and inclusivity of gays and lesbians, the transgender community is still very much plagued by discrimination in society. Transgender and non-binary scientists may receive more harassment than their colleagues. Extra support from the community is needed to ensure the physical and psychological safety of these members of the nuclear physics community. The use of pronoun identification for meetings and conferences as well as in one's email signature is an example of simple things that create an inclusive and respectful environment. Additionally, implementation of non-gendered bathrooms can have a substantial improvement on transgender and non-binary members' daily lives. This can be implemented through

changing single-stall restrooms to all-gender or providing sanitary products in the men’s restroom as well as the women’s. Furthermore, making resources easy to access can also be beneficial. At Pacific Northwest National Laboratory, a series of Transgender Resource Guides have been made publicly available [Pac2022]. These guides detail various available resources for transgender staff and managers to understand inclusive practices, benefits, recommended timelines/resources to aid employees who are transitioning or have transitioned.

Towards more inclusive practices for transgender and non-binary members of the community, in 2021 all seventeen U.S. national laboratories came together with a variety of publishing agencies to streamline name changes in publication records [Ner2021]. As many of the top publishing agencies are included in this effort, academic institutions could potentially offer a similar service.

RECOMMENDATIONS

Below are several recommendations towards improving inclusivity in nuclear physics for the LGBTQ+ community from the Town Hall on Nuclear Structure and Astrophysics:

- Perform a new climate survey to better understand the status for LGBTQ+ members of the community.
- Create and support LGBTQ+ employee/support groups within institutions to foster community/belonging and provide resources for staff.
- Address institutional name-change policies (as well as changes in publication records).
- Promote availability and recognition of Safe Space training across academia and national laboratories.
- Increase availability of single-stall or non-gendered restrooms across institutions and ensure their availability at meetings and conferences.
- Normalize the use of single pronouns for communication.
- Normalize the use of pronouns in email signatures and name badges for meetings and conferences.

FINANCIAL STRESS ON GRADUATE STUDENTS

Current graduate students in physics earn salaries significantly below a living wage (see Figure 6.2, left), and lower than many jobs they could get with a physics Bachelor’s degree (see Figure 6.2, right). In all disciplines, approximately 1 in 4 graduate students experienced housing or food insecurity [APSNews2022].

“If indeed diversity, equity, and inclusion are central to our vision of physics’ future, then science institutions must look beyond those who have traditionally had access to more resources. To support scientists of diverse backgrounds or non-traditional career [paths], we must advocate for stronger financial support for graduate students, who are invaluable employees for universities.” Graduate student pay is an equity issue. It impacts under-represented groups disproportionately: “The consequences of underpayment do not hurt everyone equally. Graduate programs that do not pay students living wages will push away bright minds who come from less wealthy or marginalized backgrounds.” [APSNews2022].

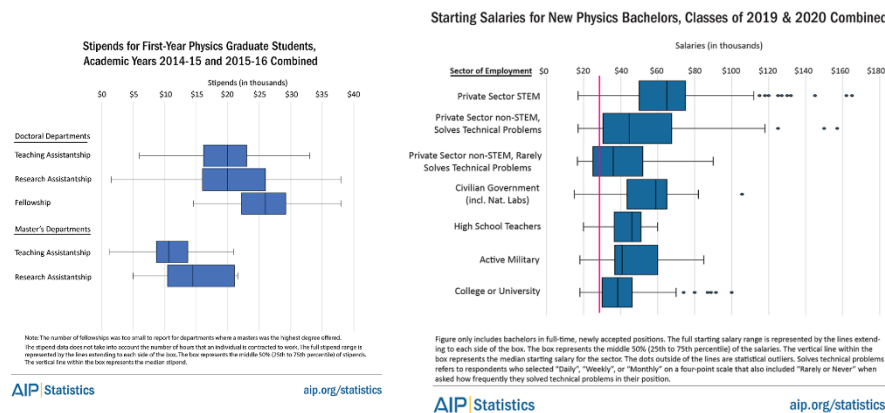


Figure 6.2: (Left) First-year physics graduate school salaries 2014-2016. (Right) Physics bachelors, starting salaries 2019-2020. The red line corresponds to the upper end of the fellowship recipient salaries, which still fall far below salaries available to students in the workplace.

According to the DOE Office of Science, the appropriate living wage for graduate students corresponds to an annual salary of \$45k/yr [DOELW], far above wages currently earned by graduate students (see Figure 6.2, left). Other important resources needed by struggling graduate students include a waiving of application fee (typically \$75/school), making the Graduate Record Examination (GRE) permanently optional (which currently costs \$150/attempt), the awarding of signing bonuses and/or paid moving expenses, funds for paid parental leave, supplements made available for graduate students who are parents, and cash advances made available to graduate students before their first work travel (to offset delays incurred by administrative reimbursement delays that can stretch a student's personal finances). Graduate students are not only students in training, but they provide extraordinary value to universities as employees. They deserve to be paid accordingly.

RECOMMENDATIONS

- Pay undergraduate students >\$15/hr.
- Make graduate applicant fee waivers an easy request available to those in need.
- Make Physics GRE optional permanently to reduce financial burden on applicants.
- Make moving expenses or signing bonuses for incoming graduate students allowable costs for federal grant proposals (DOE, NSF).
- Pay our graduate students a living wage [MIT2022], request \$45k/yr/grad in grant proposals.
- Grant graduate students 6 weeks paid parental leave when they become parents.
- Increase graduate students wages by \$3k/yr/child for graduate students who are parents.

OUTREACH INITIATIVES TO STRENGTHEN AND DIVERSIFY NUCLEAR SCIENCE

The nuclear physics community needs to devote time and effort to understand minority and marginalized communities better to sustain programs that enable pathways to diversify the workforce. Institutions have unique opportunities and resources that could be transformative for these communities, but they should reflect on why someone would want to come to their institution: students and/or faculty should feel like they are at home! While education should be rigorous, the human component must be present. Providers and stakeholders must do more for students from these communities that have the potential of becoming the next generation nuclear scientists, noting that resources have diminished over the years and the majority of the funding has been directed to other areas than physics.

Workforce recommendations from Rising Above the Gathering Storm [NAS2007] focused on improving K-12 STEM education, as well as providing incentives for students to pursue STEM education at the undergraduate and graduate levels. However, by themselves, these are insufficient to meet the emerging demographic realities. The United States stands at another crossroad: “A national effort to sustain and strengthen STEM must also include a strategy for ensuring that one embraces the minds and talents of all Americans, including minorities who are underrepresented in STEM and currently embody a vastly underused resource and a lost opportunity for meeting the nation's technology need.”

Data from the Higher Education Research Institute at UCLA have shown that, upon college entry, underrepresented minorities intend to major in STEM at the same rates as their white and Asian American peers. Yet, these underrepresented minorities have lower four- and five-year completion rates relative to those of whites and Asian Americans [NRC2015]. This problem cannot be solved by financial assistance alone. Researchers have shown that financial incentives are most effective in reducing attrition among low-income and minority students when provided in conjunction with academic support and campus integration programs [NRC2015, AIP2020]. The culture and climate of institutions, including the diversity of faculty, impact the entire process from entry to graduation. At both the undergraduate and graduate level, engagement in rich research experiences allows for the development of interest and competence in, and identification with STEM, and enhances academic competitiveness.

Physics programs have consistently ranked near the bottom among all disciplines in their ability to attract and retain under-represented groups [Mer2015, Mer2019]. Increasing the participation and success of underrepresented minorities in science and engineering contributes to the health of the nation by expanding this talent pool, enhancing innovation, and improving the nation's global economic leadership. Despite many successful programs established within the past decades to increase the representation of under-represented groups in physics [APSBridge, FisBridge, MtiSTEM], their impact in nuclear physics is still sadly insignificant.

MINORITY SERVING INSTITUTIONS: Minority-serving institutions (MSIs), specifically Historically Black Colleges and Universities (HBCUs) and Hispanic Serving Institutions (HSIs), have proven to be important vehicles to Black and LatinX students attaining access to and participating in the STEM career pipeline [Cru2019, Cul2009, Gar2011, Gas2017, Gas2014, Owe2012]. Though this is the case, it is also true that often these institutions provide this access with fewer resources than their non-MSI counterparts [Cun2014, Jon2014, Li2018]. Scholars have attempted to theorize what makes MSIs such as HBCUs and HSIs able to produce such a sizeable proportion of Black and LatinX STEM students [Owe2012, Pal2013, Pal2010, Per2009].

The funding level at MSIs is orders of magnitude smaller than Research 1 (R1) institutions, albeit many faculty members are still conducting a very high level of research and sustain an impressive publication record. Furthermore, research is historically and usually not the priority at these institutions, while teaching and students are, with teaching load exceeding three courses/semester [AIP2020]. For the latter, attention to students is the top priority: faculty will spend a considerable amount of their time mentoring, leaving little time for research. However, such an approach has proven to support student retention and to provide students with a solid foundation to push through difficulties throughout their education and career paths with many becoming highly successful. Unfortunately, R1 institutions too often rely on a very small number of people to carry the DEIB load which is not sustainable.

The role and impact on increasing the sense of belonging were recently highlighted at the 2022 Fall meetings of the American Physical Society Division of Nuclear Physics [DNP2022] and National Society of Black Physicists [NSBP2022]. One of the main outcomes is that NSBP seems to provide a more “comfortable” environment for students and professionals to interact beyond the science: “you are not as free at APS, you know what I mean?” (high school

student), “people come and talk to you at NSBP; it is more relaxed” (postdoc), and “now I know what you all meant when talking about being inclusive” (faculty). The NP community is ignoring some “lower level” conferences and workshops that are priority for marginalized groups (NSBP [NSBP2022], SACNAS [SACNAS], ERN [ERNC] ...) compared to the more “standard” ones (APS/DNP [DNP2022], APS/April [APSApril], CAARI [CAARI], IPAC [IPAC2023] ...). The sense of trust building between communities is critical and failing to attend these events has had the adverse effect of making such communities feel less welcome.

RECOMMENDATIONS

- Increase support and foster collaborations between MSIs and R1 institutions, national laboratories, and user facilities.
- Enable collaborations between Technical and Community Colleges and R1 institutions, national laboratories, and user facilities.
- Support programs that target parents from under-represented and marginalized communities and educate them about the role of basic and applied nuclear science in society.
- Enable physics minors that include cross-disciplinary degrees from basic and applied to dual degrees with non-STEM disciplines such as history, medicine, art etc.
- Create a three- to four-week undergraduate-focused summer school to complement existing programs such as the Nuclear Science Summer School (NS3) [NS3] that would include lectures and hands-on material for inspiration, recruitment, and retention.
- Provide funding support to hire outreach coordinators at Minority Serving Institutions (MSIs) and Primary Undergraduate Institutions (PUIs).
- Increase student and teacher programs at the pre-college level for under-represented and marginalized communities.
- Create emergency funding mechanisms to provide needs outside of educational goals.

DEIB INITIATIVES IN NUCLEAR SCIENCE

In nuclear science there are several groups and programs designed for the promotion of DEIB for the formation of a more equitable, inclusive, and welcoming nuclear science community. Some examples of these efforts are briefly described below.

DNP DIVERSITY, EQUITY, AND INCLUSION (DEI) COMMITTEE: The DEI committee of the DNP undertakes activities that promote diversity, equity, and inclusion in nuclear science. They oversee the Allies Program (described in greater detail in Harassment in Nuclear Science), in which several vetted and trained DNP members make themselves available to anyone at the fall DNP meetings who believes they may have experienced harassment. Allies are non-mandatory reporters who provide a safe space for victims to report their experience, receive support and encouragement, and options to consider moving forward. The DEI committee also administers a yearly survey to the DNP community to measure and monitor the DEI climate in nuclear science, they organize sessions at fall DNP and spring APS meetings to address ongoing challenges in the community and oversee the DNP ambassadors program to establish greater connections between the DNP and other professional societies such as the NBSF. Finally, the DEI committee provides training for all fall DNP and spring APS meeting session chairs to equip them with techniques and tools to advance DEI goals at the meetings.

THE GENDER MINORITIES IN SCIENCE SOCIAL (GEMSS): The Gender Minorities in Science Social (GeMSS) is a networking event that is currently hosted annually in conjunction with the Fall Meeting of the DNP. This event aims to create a safe and inclusive environment and to also foster mentorship opportunities for those identifying as a

gender minority in science, particularly for early career scientists. Currently, the event is held as a working lunch with 3-4 speakers that cover early, mid, and late career-stages with time for questions and networking amongst peers. Over the years, the event has gained in popularity, with the 2019 virtual event playing host to over 100 people. This trend has continued in person with an attendance of almost 100 people in 2022. To enable accessibility for early career scientists, attendance of CEU students at this event is generously sponsored by a combination of senior sponsorship and the NNSA center of excellence, CENTAUR.

This event has had enormous success as a grass-roots movement by early career scientists. As it has expanded and grown, we have consistently received positive feedback from our attendees with one person saying that her attendance at the 2019 event was a key factor in her decision to pursue a physics career [Sap2021]. Looking towards the future, funding secured through DNP will allow for expanded attendance and to create a bigger network of participants, potentially even expanding to other APS meetings. Reflecting on the successes of this event demonstrates that giving early career scientists the opportunity to create an open and inclusive space will undoubtedly have a positive impact, and more opportunities like this are needed.

PHYSICISTS INSPIRING THE NEXT GENERATION (PING) AT MSU: The PING program was launched in 2014 as a collaboration between the National Society of Black Physicists (NSBP) and the National Radio Astronomy Observatory (NRAO) in partnership with Associated Universities, Inc. PING is a program that targets both pre-college students and undergraduate students (who serve as mentors). The program involves a two-week experience in nuclear physics at FRIB with the potential to turn into a year-long real research experience. Students present their work at the National Society of Black Physicists and the American Physical Society Division of Nuclear Physics conferences [PING].

FRIB PAC2 GUIDELINES: The second solicitation of proposals for experiments at the Facility for Rare Isotopes (FRIB) at Michigan State University (PAC2) now includes an additional section in which PIs are to describe the collaboration organization and their plans for creating an encouraging atmosphere for all. This section is to include a description of responsibilities for all participants, a procedure for managing conflicts, and how the collaboration will interface with the lab. In addition, FRIB has implemented a Research Code of Conduct, which includes a mechanism to investigate reports of misconduct [FRIBPAC2].

ARGONNE LAB DEI COMMITTEE: The Argonne National Laboratory's DEI committee in the Physics Division was formed in part to bring awareness to current opportunities and challenges that impact DEIB in the local culture [ANL2022]. The committee has advocated for an increased number of DEIB-related talks in colloquia, restroom renovation in ATLAS to accommodate users, collection of demographics for PAC proposal submissions, and a feasibility study for a blind review process for ATLAS proposals. They also underscore the challenge of sustainability for those involved in DEIB efforts and recommend that such efforts be included in employee performance evaluation.

CICADA AT TEXAS A&M UNIVERSITY: The Cyclotron Institute Cultural Awareness and Diversity Assembly (CICADA) at Texas A&M University [CIC2022] was formed in early 2022. The group administers surveys to the Cyclotron Institute (CI) community at TAMU to promote a welcoming and inclusive environment for all CI members and visitors. The committee plans to administer surveys every 1-2 years for the purpose of assessing progress of the committee's initiatives. They formed a seminar series entitled "Cyclotron Institute Community Building Discussions", which invites communal conversation on topics important to the promotion of DEIB, such as Title IX procedures and policies, LGBTQ+ culture at CI, to make a better workplace for all. CICADA is also contributing to improvement of the CI Code of Conduct and to the development of policies to deal with violations of the Code [CIC2022].

BROOKHAVEN LAB PRIDE ALLIANCE: The Brookhaven Lab Pride Alliance serves as a resource to individuals identifying as a gender or sexual minority (GSM) in the research environment. They provide advocacy for non-heterosexual and gender non-conforming individuals at BNL, foster connections with surrounding LGBTQ+ networks, and provide educational and cultural programs for support of individuals and their families [BNL2022]. The Pride Alliance has developed programs to help combat closet culture at the lab and educate the general population regarding LGBTQ+ issues. They've provided training, hosted lecturers, run regular meetings, launched an allyship group, and challenged policy at BNL (regarding bathrooms, transgender fertility services, gender affirming surgery, name changing, etc.).

PHYSICS SUMMER CAMP MISSISSIPPI STATE UNIVERSITY: The Physics Summer Camp for students with Autism Spectrum Disorder (ASD) at Mississippi State University was developed in partnership with local agencies and clinics. It provides students with ASD who are interested in physics and STEM fields with an inclusive postsecondary transition program that includes lectures, hands-on demonstrations, and interactive lab activities [Cri2022].

FUNDING AGENCIES FOR NUCLEAR SCIENCE: The two major funding agencies for nuclear science, the Department of Energy (DOE) and the National Science Foundation (NSF), are both committed to efforts devoted to increasing DEIB in nuclear science [DOEDEI, NSFDEI]. Research proposals submitted to DOE are now required to include a plan for Promoting Inclusive and Equitable Research (PIER) which describes specific activities and strategies designed for promoting diversity, equity, inclusion, and accessibility in the research program [DOEDEI].

While efforts such as those listed here seek to advance DEIB goals across nuclear science, they will be much less effective if individuals are allowed to harass and bully community members without consequence, resulting in the departure of talent from nuclear science.

HARASSMENT IN NUCLEAR SCIENCE

The scientific enterprise benefits from participation of a broad and diverse community. Participants from under-represented groups draw new relations between ideas and concepts that lead to increased innovation [Bar2022]. To the extent that harassment and bullying of members in the nuclear science community persist, and are tolerated by those in leadership, the field (and its individuals) will suffer, and fail to reach its full potential for discovery and advancement of nuclear science.

Federal law already prohibits discrimination and harassment based on gender in the workplace [TitleVII]. Additionally, recipients of federal financial support are prohibited from allowing harassment and discrimination of individuals based on sex and gender identity [OCR2022]. According to the APS Guidelines on Ethics Statement [APS2022], "Abuse of colleagues, students, or subordinates degrades the conditions for honest interchange that lead to the best scientific ideas and support the scientific enterprise." For nuclear science to thrive and conduct its best science, the community needs to become increasingly diverse, and cultivate and sustain an environment in which all feel included and welcome.

PARTICIPATION OF WOMEN IN PHYSICS: According to the AIP, the current percentage of women earning bachelor's degrees in physics is low, hovering at or below 20% [AIP2019]. Figure 6.3, left, includes data from 1977 to 2017, and while gains have been made over the years, current numbers of undergraduate women in physics is still very low, and has even dropped by 2-3% since 2001. The percentage of women earning PhDs is also low compared with men, and while gains have also been made for these degree recipients, representation of women is significantly behind those earning PhDs in all physical sciences and in all fields combined (Figure 6.3, right), pointing to a serious and ongoing concern for the physics community.

In 2018 the National Academy of Sciences released a report entitled *Sexual Harassment of Women, Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine*, in which they document the significant persistence of sexual harassment in Academic Sciences and STEM-related fields [NAS2018]. They note that while gains have been made over several decades to increase the participation of women in science, engineering, and medicine, sexual harassment nonetheless persists, causing women to leave the fields, and creating a significant barrier to the goal of achieving equity [NAS2018].

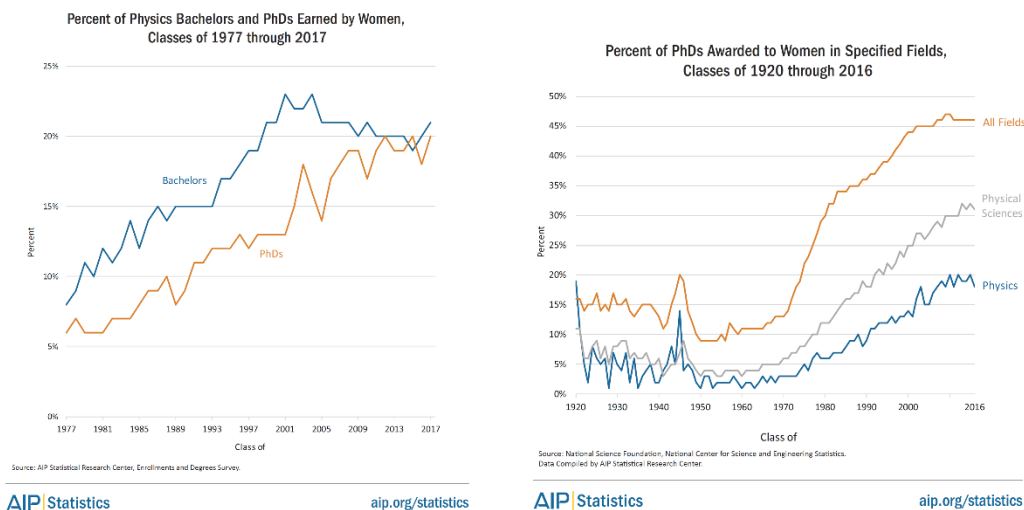


Figure 6.3: (Left) Percent of Bachelor degrees and PhDs earned by women from 1977 to 2017. (Right) Percent of PhDs awarded to women in physics from years 1920-2016, compared with physical sciences in general, and all fields [AIP2019].

According to the National Academies 2018 report, the occurrence of sexual harassment in physics, and tolerance for it among those in leadership is the main contributor to the persistence of low representation of women in physics. Participation rates of women in nuclear science are at similar levels compared to physics generally. Membership of women in the DNP has increased from approximately 12% to 18% over the last 10 years, while APS fellow appointments going to DNP women are significantly lower (approximately 4-9% going to women over the same years) compared with their male counterparts.

TYPES OF SEXUAL HARASSMENT: Sexual harassment is broadly defined as unwelcome or inappropriate behavior of a sexual nature that creates an uncomfortable or hostile environment [Lib2019]. The National Academics 2018 report defines three types of sexual harassment: 1) Gender Harassment - verbal and nonverbal behaviors that convey hostility to, objectification of, exclusion of, or second-class status about members of one gender. This includes off-color jokes referencing people of a protected category. 2) Unwanted Sexual Attention - verbally or physically unwelcome sexual advances, which can include assault. 3) Sexual Coercion - when favorable professional or educational treatment is conditioned on sexual activity [NAS2018].

The report points out that some of the highest profile cases in recent years have been in higher education and STEM-related fields. These areas create high levels of risk and enable sexual harassment to persist because 1) higher education has long been male-dominated environment with men in most positions of power, 2) higher education has historically been perceived to tolerate and/or cover up sexually harassing behavior, 3) structures are hierarchical

with dependent relationships between faculty and students, postdocs, residents, and 4) work is often done in isolated environments [NAS2019].

Physics at universities and national laboratories has long been male-dominated, with men in most positions of leadership. This creates a situation in which harassment of women is likely. Evidence of ongoing and persistent sexual harassment exists in physics, as well as in nuclear science, some of which is summarized below.

EVIDENCE OF SEXUAL HARASSMENT IN NUCLEAR SCIENCE: Sexual harassment occurs in the nuclear science community, and if left unchecked, will continue to result in the unfortunate departure of good talent from the field. The following examples point to areas of concern for the treatment of women of all stages of their professional career.

CUWiP PARTICIPANT EXPERIENCES - A survey was administered to the 2017 participants of the Conference for Undergraduate Women in Physics (CUWiP) conferences, of which 500 attendees responded. Approximately 75% of respondents reported experiencing at least one type of sexual harassment of sufficiently negative impact as to correlate with a sense of not belonging to the field [Ayc2019]. Of these, more than 90% experienced sexist gender harassment (hostile words or behavior based on target's gender), a third experienced sexual gender harassment (commenting on a woman's looks, body shape, etc.), and a third experienced unwanted sexual attention. The study found that the sexual harassment experienced by these women correlated with a negative sense of belonging, and often exacerbates the imposter syndrome in its victims [Ayc2019]. It's not hard to see why these kinds of experiences at such a young age result in talented students leaving physics.

As a result of these experiences for young female students in physics, "[w]hen sexual harassment goes unchecked, physics loses great people, great minds, and great potential. It's [also] worth noting that sexual harassment disproportionately affects people of color, people with disabilities, and members of the LGBTQ+ community" [Lib2019].

CEU STUDENT EXPERIENCE AT DNP MEETINGS - Some participants in the Conference Experience for Undergraduates (CEU) program at the fall DNP meetings have experienced sexual harassment of serious enough impact to drive them from nuclear science. Female CEU students have reported being leered at by men of all ages, being targets of unwanted and prolonged attention during the poster session, receiving requests to take their pictures, and experiencing unwanted sexual attention including physical touching and groping [Rog2022]. Notably several of these reports involved actions by senior, well known members of the community. As an example, one female student reported hopes of pursuing graduate work with a particular group at one of the national laboratories, but after experiencing unwanted sexual attention from a mid-career and well known DNP member who works in close proximity to that group, she reluctantly abandoned hopes of joining that group and pursued her graduate studies at a different university in a field outside of nuclear science. Other students experiencing unwanted attention from male DNP members were impacted seriously enough to consider moving to another subfield of physics or to leave physics altogether. These few reported student experiences, likely the tip of a much larger iceberg, should signal a deeply concerning alarm for the nuclear science community.

DNP DEI COMMITTEE SURVEY - In 2022, a survey was administered by the DNP Diversity, Equity, and Inclusion (DEI) committee to members of the DNP. A simple question was asked, "While in a professional setting (such as university, lab, institute, or conference) how often in approximately the past 12 months have you felt uncomfortable because of your gender?" [DNPDEI2022]. Results are summarized in Figure 6.4, which shows that 2% of men reported experiencing 1-5 incidents in the past year, compared with 54% of women. Numbers for the LGBTQ+ community exhibit an even stronger disparity compared with men.

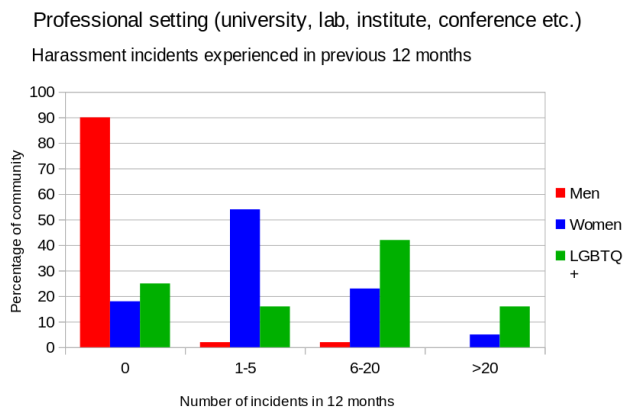


Figure 6.4: Results from 2022 survey administered by the DEI committee of the DNP [DNPDEI2022]. Women and members of the LGBTQ+ community are much more likely to be the victims of sexual harassment.

IMPRESSIONS OF A DNP MEETING BY SARA JANE - Since the DNP Allies program began in 2017, several individuals who have experienced sexual harassment and bullying from physicists in nuclear science have shared their painful experiences with the DNP Allies. A collection of these stories has been made available (anonymously) on the Allies program webpage in an effort to raise public awareness about the prevalence and severity of wrongful behavior by our own DNP colleagues, especially for skeptics who do not believe harassment occurs at fall meetings. These anecdotes are cast as if they were experienced by an individual named Sara Jane while navigating a fall DNP meeting [DNPSaraJ]. Experiences included in this 'diary' are reported by women of all ages and professional status within the DNP, and should be of serious concern for us all.

These examples of harassment experienced by women and gender minorities of all ages and professional status in nuclear science point to a serious concern for our community, in need of solutions that will truly change our culture for the better. Allowing harassment to continue drives women and under-represented minorities from our field, which hurts the field of nuclear science and blunts our scientific progress.

A WAY FORWARD: To create and sustain a more inclusive, equitable, and welcoming community, changes to our organizational climate are necessary. To realize this goal, according to the National Academies Report [NAS2018], organizations must

- Provide support for targets of harassment.
- Demonstrate publicly and believably that harassment behavior is unacceptable.
- Develop policies and procedures to hold perpetrators accountable.
- Make bystander training available to all.
- Change funding and mentoring structures, if necessary.
- Provide opportunity for targets to speak with non-mandatory reporters (such as the DNP Allies).
- Provide appropriate tools to administrators to combat and handle harassment incidents.
- Demonstrate publicly that people who harass will be held responsible.

Several examples of initiatives seeking to increase diversity in nuclear science and make it a more inclusive, welcoming community are included in the 'DEIB Initiatives' section of this paper. These initiatives alone, while helpful in diversifying our community and providing support for the underprivileged, will not lead to lasting change as long as we do not collectively embrace and put into action these important NAS recommendations.

FORMATION OF THE DNP ALLIES PROGRAM: When news of CEU student harassment experiences at fall DNP meetings was reported to the DNP Executive Committee, the ad-hoc DNP Committee on Harassment Prevention (CHP) was formed. To provide conference attendees who experience harassment a safe place to report and talk about their experience with a non-mandatory reporter (in line with the NAS recommendation [NAS2018]), the CHP proposed creating the DNP Allies Program [DNPAllies], modeled after a similar program in the astronomy community. DNP Allies are drawn from DNP members and are vetted and trained to assist participants at the fall meetings who believe they may have experienced harassment, by providing a safe space for reporting their experiences, and offering options and possible resources, including assistance in determining further steps that may be warranted. The APS also provides a representative to attend the fall meetings to address Code of Conduct (<https://www.aps.org/meetings/policies/code-conduct.cfm>) issues that arise.

The first DNP Allies Program was held at the 2017 fall DNP meeting, with CHP members serving as the first cohort of Allies. The program has been run at each fall meeting since then, and the number of Allies has expanded to its current number of approximately 30. The number and types of harassment incidents recorded each year by the Allies have reduced over time, while expressions of appreciation for the work of the Allies have notably increased. Given the success and importance of the DNP Allies program in nuclear science and the many expressions of appreciation and support for the program from community members, we recommend the expansion of the DNP Allies Program at Spring APS meetings and the promotion of its adoption in other APS units.

CODES OF CONDUCT: Recognizing the importance of creating and sustaining a more welcoming and inclusive environment for everyone in nuclear science, many organizations (collaborations, universities, departments, laboratories, professional societies, funding agencies ...) have in recent years adopted a Code of Conduct (CoC). CoCs provide baseline expectations for how community members interact with others, treating one another with dignity and respect regardless of personal origins or characteristics, and free from any form of discrimination, harassment, bullying, or retaliation. Most Codes of Conduct at present do not, however, include an enforcement mechanism consisting of policies and procedures for reporting and investigating violations of the Code, and for holding offenders accountable through appropriate penalties.

Without a clear procedure for protecting victims and holding perpetrators accountable, a Code of Conduct is by itself unable to reduce or eliminate the persistence of harassment. In fact, the establishment of Codes of Conduct have in some cases produced unforeseen negative consequences [Bar2022b]. According to the National Academies [NAS2018], the likelihood of harassment occurring in an organization is correlated with three climate “predictors,” which include:

- The perception of risk on behalf of victims wanting to report harassment.
- The perception that reports will not be taken seriously by leadership.
- A lack of appropriate sanctions for offenders.

COMMUNITY AGREEMENTS: By now it has become clear that Codes of Conduct alone will not produce the substantive and meaningful change necessary in physics [NAS2018]. When organizational leadership fails adequately to confront the problem of harassment, when clear policies and procedures are absent that make it plain that harassment and retaliation will not be tolerated at any level, and where reports of harassment receive minimal or performative response, harassment will continue, and individuals will be hurt. When protection for victims from retaliation is weak or absent, where jokes marginalizing protected categories are allowed to persist and define the communal atmosphere, and where sexual harassment training is insufficient or not taken seriously, women and gender minorities will continue to suffer, and many will choose to leave the field.

To create and sustain a more diverse, equitable, inclusive, and welcoming community for all individuals in nuclear science, Codes of Conduct must include clear policies and procedures for dealing with violations of the Code, resulting in what have come to be called Community Agreements (CA) [Bar2022b]. All physics organizations in nuclear science must move beyond mere legal compliance, and proactively craft and adopt policies that enable victims to be protected, and for incidents of harassment to be adjudicated with transparency and accountability [NAS2018].

Excellent resources are available for help in the crafting and execution of Community Agreements, including from the APS Division of Particles and Fields (DPF) in “DPF Core Principles and Community Guidelines” and “DPF Code of Conduct Accountability” [DPF2020a, DPF2020b] and from a white paper by Barzi *et al.*, entitled “How Community Agreements Can Improve Workplace Culture in Physics” [Bar2022b]. Community agreements should include a clear list of expectations for individual behavior, a team of individuals with the responsibility of receiving and processing reports of misconduct, and an enforcement mechanism that uses equitable and unbiased standards for investigating complaints and applying appropriate penalties [Bar2022b]. A Community Agreement should also include support for victims and protection from retaliation, as well as a means of assessing progress by the application of, for example, annual surveys to the community. We strongly recommend that all physics organizations adopt Community Agreements, and that compliance with that agreement be explicitly required as a condition of membership in that organization.

INDIVIDUAL RESPONSIBILITIES: The work of creating and sustaining a diverse, equitable, inclusive, and welcoming community in nuclear science is the responsibility of every individual in the community. Each one of us needs to be an agent of change for any real progress toward our DEIB goals. Several men interviewed by DNP Allies have expressed skepticism regarding the presence and persistence of harassment and bullying in nuclear science. Additionally, some white males who identify as progressive and are concerned about the prevalence and negative impact of harassment “express patterns of belief, speech and (in)action that ultimately justify the status quo of white male privilege, locating causes of inequity in large societal systems over which they have little influence” [Dan2022].

Better education on harassment and its negative effects on individuals and the community, especially for men in positions of privilege who either fail to recognize the problem of harassment, or who acknowledge it but believe they are largely powerless to effect change, is critical to making real and lasting progress. Each member of our community has a duty and responsibility to assist. We offer here several recommendations for educating and equipping individuals to be agents of change.

- Become better educated on the presence of harassment in nuclear science and on its toxic effect on individuals and the community.
- Honestly assess our individual behavior and its impact on others.
- Examine outdated assumptions from the past and recognize changes in cultural norms.
- Receive bystander training and be prepared to intervene when necessary.
- Be a listener, encourager, and helpful resource to victims of harassment, and take them seriously.
- Don’t let any personal attacks go unchallenged.

At the 2022 APS April meeting, Tim Hallman, Associate Director of Nuclear Science in the DOE Office of Science, acknowledged that while more serious incidents of misconduct such as inappropriate touching, physical assault, and behavior bordering on criminal do occur, they may in the end be less impactful than “continued dismissive behavior based on gender, ... inappropriate or nonprofessional remarks based on gender ... [and] microaggressions based on gender” in damaging progress toward the community’s DEIB goals [Hal2022]. He went on to say, “This is not who

we are and aspire to be as a society of talented professionals/intellectuals” and “[t]he only thing it takes for bad-behavior defeating DEI goals to continue is for people of good conscience and integrity to do nothing.” We couldn’t agree more.

RECOMMENDATIONS

- All members of the nuclear science community are urged to become familiar with the presence and effects of harassment in our community.
- All members are urged to assess the impact of their individual behaviors.
- Bystander training should be made available at all DNP conferences and workshops.
- All physics collaborations should be required to adopt Community Agreements, which include expectations for community members’ behavior and a process for reporting and investigating incidents, and an effective and transparent mechanism for enforcement of consequences for misconduct.
- We recommend the expansion of the DNP Allies Program at Spring APS meetings and the promotion of its adoption in other APS units, as well as offering bystander training at APS meetings.
- We recommend that DEI plans be integrated into all grant proposals with grants renewal re-assessed based on DEIB performances.

We recommend that community climates be measured annually through anonymous surveys to assess and improve on the impact of DEIB efforts.

BIBLIOGRAPHY

[AIP2019] Women in Physics and Astronomy, Anne Marie Porter and Rachel Ivie, [<https://www.aip.org/statistics/reports/women-physics-and-astronomy-2019>]

[AIP2019a] African-American Participation Among Bachelors in the Physical Sciences and Engineering, Laura Merner and John Tyler, [<https://www.aip.org/statistics/reports/african-american-participation-among-bachelors-physical-sciences>]

[AIP2020] The AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP). “The time is now: systemic changes to increase African Americans with bachelor’s degrees in physics and astronomy,” (2020). [<https://www.aip.org/diversity-initiatives/team-up-task-force>]

[AIP2021] Results from the 2019 Survey of Enrollments and Degrees and the Degree Recipient Follow-up Survey for the Classes of 2017 and 2018, Patrick J. Mulvey, Starr Nicholson, and Jack Pold. [<https://www.aip.org/statistics/reports/>]

[ANL2022] Diversity and Inclusion at Argonne National Laboratory, [<https://www.anl.gov/diversity-and-inclusion>]

[APS2018] APS in the #MeToo Era, Warren Rogers, Roxanne Springer, Sherri Yennello, APS Back Page. [<https://www.aps.org/publications/apsnews/201808/backpage.cfm>]

[APS2022] APS Guidelines on Ethics (2022). [<https://aps.org/policy/statements/guidelinesethics.cfm>]

[APSApril] American Physical Society April Meeting. [<https://april.aps.org>]

[APSBridge] American Physical Society Bridge program. [<https://www.aps.org/programs/minorities/bridge/index.cfm>]

[APNews2022] Graduate Students Should Be Paid Living Wages, Jacqueline Acres, The Back Page, APS News, 31, 11 (2022)

[Ath2016] LGBT Climate in Physics: Building an Inclusive Community, T. J. Atherton, R. S. Barthelemy, W. Deconinck, M. L. Falk, S. Garmon, E. Long, M. Plisch, E. H. Simmons, K. Reeves, American Physical Society, 2016. [<https://www.aps.org/programs/lgbt/upload/LGBTClimateinPhysicsReport.pdf>]

[Ayc2019] Sexual Harassment Reported by Undergraduate Female Physicists, Aycock *et al.*, Phys Ref C PER 15, 010121 (2019).

[Bar2022a] In Search of Excellence and Equity in Physics, Barzi, Gates Jr., Springer (APS CSWP & COM Gazette vol. 41 No. 1). [<https://doi.org/10.48550/arXiv.2203.10393>]

[Bar2022b] How Community Agreements Can Improve Workplace Culture in Physics, Emanuela Barzi, Simonetta Liuti, Christine Nattrass, Roxanne Springer, Charles H. Bennett. [<https://doi.org/10.48550/arXiv.2209.06755>]

[BNL2022] Brookhaven Laboratory Pride Alliance. [bnl.gov/pridealliance]

[Bru2019] KL Brue, Journal of Leadership Education 18 2 (2019), https://journalofleadershiped.org/wp-content/uploads/2019/04/18_2_brue.pdf

[CAARI] Conference on the Application of Accelerators in Research and Industry (CAARI). [<https://caari-sneap.com/home>]

[CIC2022] CICADA. [<https://cyclotron.tamu.edu/cicada/>]

[Cri2022] Ben Crider, Mississippi University, Physics Summer Camp for Students with ASD. [<https://www.physics.msstate.edu/webform/physics-summer-camp-students-asd>]

[Cul2009] J. Cullinane and L. H. Leegwater. Diversifying the STEM Pipeline: The Model Replication Institutions Program. Institute for Higher Education Policy, 2009.

[Cun2014] A. Cunningham, E. Park, and J. Engle. Minority-serving institutions: Doing more with less. Institute for Higher Education Policy, 2014.

[Cru2019] C. Cruz, G. Rajpal, M. Lecocke, I. Martines, and A. Lurie. Peer coaching program development: A framework of first-year Latina/o student persistence pursuing stem pathways at a Hispanic Serving Institution. Journal of Hispanic Higher Education, 0(0):1538192719867096, 2019.

[Dan2022] How well-intentioned white male physicists maintain ignorance of inequity and justify inaction, Melissa Dancy, Apriel Hodari. [<https://doi.org/10.48550/arXiv.2210.03522>]

[DNPDEI2022] DNP DEI committee survey administered to the DNP community in 2022.

[DNP2022] American Physical Society Division of Nuclear Physics 2022 Fall Meeting. [https://meetings.aps.org/Meeting/DNP22/APS_epitome#all]

[DNPAllies] [<https://engage.aps.org/dnp/governance/about/allies-program>]

[DNPSJane] Impressions from the DNP Fall Meeting by Sara Jane, DNP Allies. [<https://engage.aps.org/dnp/governance/about/allies-program/dear-diary>]

[DOEDEI] [<https://www.energy.gov/science/diversity-equity-inclusion>,
<https://www.energy.gov/science/articles/everyone-has-role-play-making-science-more-equitable-and-inclusive>]

[DPF2020a] DPF Core Principles and Community Guidelines [<https://drive.google.com/file/d/1dE1-Qm4iZfzWVo8L97Cpz1UnOjOkQ2mm/view>]

[DPF2020b] DPF Code of Conduct Accountability. [<http://seattlesnowmass2021.net/assets/docs/DPF-CPCG-05.03.2022.pdf>]

[ERNC] Emerging Researchers National Conference in STEM. [<https://emerging-researchers.org>]

[FisBridge] Fisk University and Vanderbilt University. Fisk-Vanderbilt master's-to-PhD program. [<https://www.fisk-vanderbilt-bridge.org>]

[FRIBPAC2] [<https://frib.msu.edu/users/pac/guidelines.html>]

[Gar2011] G. A. Garcia and S. Hurtado. Predicting Latina/o STEM persistence at HSIs and non-HSIs. University of California, Los Angeles, 2011.

[Gas2014] M. Gasman and T. Nguyen. Historically black colleges and universities (HBCUs): Leading our nation's effort to improve the science, technology, engineering, and mathematics (stem) pipeline. 2014.

[Gas2017] M. Gasman, T. H. Nguyen, C. F. Conrad, T. Lundberg, and F. Commodore. Black male success in stem: A case study of Morehouse College. *Journal of Diversity in Higher Education*, 10(2):181, 2017.

[Hal2022] Toward Inclusive Excellence in Nuclear Science, Tim Hallman, APS April Meeting, *Bulletin of the American Physical Society* 76 6 E04.00003 (2022).

[HRC2021] We Are Here: Understanding the Size of the LGBTQ+ Community. Report. Human Rights Campaign. December 2021. [<https://hrc-prod-requests.s3-us-west-2.amazonaws.com/We-Are-Here-120821.pdf>]

[IPAC2023] International Particle Accelerator Conference. [<https://www.ipac23.org>]

[Jon2014] T. Jones. Performance funding at MSIs: Considerations and possible measures for public minority-serving institutions. 2014.

[Li2018] A. Y. Li, D. Gándara, and A. Assalone. Equity or disparity: Do performance funding policies disadvantage 2-year minority-serving institutions? *Community College Review*, 46(3):288-315, 2018.

[Lib2019] Yes, Sexual Harassment Still Drives Women Out of Physics, J. Libarkin.
[<https://physics.aps.org/articles/v12/43>]

[Mer2015] African American participation among bachelors in the physical sciences and engineering: Results from 2003-2013 data of the national center for education statistics, L. Merner, Statistical Research Center, American Institute of Physics, 2015.

[Mer2019] L. Merner and John Tyler. African-American participation among bachelors in the physical sciences and engineering: Results from the 2005 to 2015 data of the national center for education statistics. Statistical Research Center, American Institute of Physics, 2019.

[MIT2022] [<https://livingwage.mit.edu>]

[MtiSTEM] S. Mtingwa and E. Sheppard. Interdisciplinary consortium for research and educational access in science and engineering. [<http://www.increaseonline.org>]

[NAS2007] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. The National Academies Press, Washington, DC, 2007.

[NAS2018] Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine, The National Academies of Sciences, Engineering, and Medicine (2018). [<https://doi.org/10.17226/24994>]

[NSBP2022] National Society of Black Physicists 2022 Annual Meeting. [<https://web.cvent.com/event/c58077a3-9713-402a-a64b-72f6d091e5f6/websitePage:4cebec15-0ce7-4d0b-8782-d8afaf6d638e>]

[Ner2021] Scientific Publishing Organizations and National Laboratories Partner on Transgender-Inclusive Name-Change Process for Published Papers, Matt Nerwig, News from Berkeley Lab. Lawrence Berkeley National Laboratory, July 28, 2021. [<https://newscenter.lbl.gov/2021/07/28/transgender-inclusive-name-change-process-for-published-papers>]

[NRC2015] National Research Council. Reaching students: What research says about effective instruction in undergraduate science and engineering. The National Academies Press, Washington, DC, 2015.

[NS3] Nuclear Science Summer School (NS3). [<https://nscl.msu.edu/researchers/NS3.html>]

[NSAC2022] Long Range Plan for Nuclear Science, charge letter to NSAC from DOE and NSF, 11 July 2022.

[NSFDEI] [<https://www.nsf.gov/od/oecr/diversity.jsp>]

[OCR2022] U.S. Department of Education Office of Civil Rights. [<https://www.ed.gov/category/organization/office-civil-rights-ocr>]

[Owe2012] E. W. Owens, A. J. Shelton, C. M. Bloom, and J. K. Cavil. The significance of HBCUs to the production of stem graduates: Answering the call. Educational Foundations, 26(34):33-47, Oct 2012.

[Pac2022] Supporting Transgender Staff at PNNL: A Guide for All Staff. Pacific Northwest National Laboratory. March 2022.

[Pal2010] R. Palmer, R. Davis, and T. Thompson. Theory meets practice: HBCU initiatives that promote academic success among African Americans in stem. Journal of College Student Development – J. Coll. Stud. Develop., 51:440-443, 07 2010.

[Pal2013] R.T. Palmer, D. Maramba, and M. Gasmanb. Fostering success of ethnic and racial minorities in stem: The role of minority serving. Fostering Success of Ethnic and Racial Minorities in Stem: The Role of Minority Serving, pages 1-242, 05 2013.

[Per2009] L. Perna, V. C. Lundy-Wagner, N. D. Drezner, M. Gasman, S. A. Yoon, E. Bose, and S. Gary. The contribution of HBCUs to the preparation of African American women for stem careers: A case study. Research in Higher Education, 50:1-23, 2009.

[PING] Physics Inspiring the Next Generation (PING), Michigan State University/ [<https://spartanyouth.msu.edu/Resource.aspx?ResourceID=876>]

[Rog2022] W. F. Rogers, personal communication.

[SACNAS] Society for the Advancement of Chicanos and Native Americans in Science. [<https://www.sacnas.org/>]

[Sap2021] L. Sapunar, “Fixing a Physics Culture Problem”, APS Physics. [<https://physics.aps.org/articles/v14/106>]

[TitleVII] Title VII of the Civil Rights Act of 1964, [<https://www.eeoc.gov/statutes/title-vii-civil-rights-act-1964>]

7 COMPUTING

INTRODUCTION

Computing is essential to all areas of nuclear science, enabling state-of-the-art calculations, simulations, analyses for experimental and theoretical nuclear physics, accelerator operations, and astrophysical observations. With high performance computing (HPC), nuclear physicists use every computational resource available, including leadership-class machines, high-capacity computing centers, university and laboratory clusters, and local clusters and workstations.

New technologies have also given rise to entirely new paradigms for computing that were not available a decade ago. With artificial intelligence (AI) and machine learning (ML), new algorithms are being used to learn correlations and patterns in data, accelerate calculations, make predictions with reliable error estimates, and automate machine operations. With quantum computing (QC), the large information capacity of qubits and their inherent quantum mechanical nature hold the potential for addressing long-unsolved challenges in our understanding of large and strongly entangled quantum systems.

In all these areas, progress has been accelerated by collaborations between nuclear scientists and domain scientists in computing technologies. It is crucial that investments continue to be made in these collaborations and that we train a diverse and highly skilled workforce able to capitalize on new computational technologies. As expertise in HPC, AI/ML, and QC are all in very high demand in the U.S. economy, computational research opportunities provide an important avenue for recruiting new talent to nuclear science as well as providing potential future career opportunities.

Examples of the advances in low-energy nuclear theory and astrophysics modeling enabled by HPC and AI/ML are discussed in Sec. 1 (Nuclear Structure and Reactions Theory) and Sec. 3 (Connecting Nuclei to the Cosmos). Additional examples, and opportunities for the future, were presented at the *Computational Nuclear Physics and AI/ML workshop* that was held at SURA Headquarters on Sep 6-7, 2022 (<https://indico.jlab.org/event/581/timetable/>). The status of quantum information science in nuclear physics research and its future were also the focus of the *Quantum Information Science for US Nuclear Physics Long Range Planning* workshop, held in Santa Fe, New Mexico on Jan 31-Feb 1, 2023 (<https://web.cvent.com/event/6a501e97-c61a-40bd-9c03-7f619e410eb2/websitePage:49fdd50a-9823-468a-9499-d3a920675d81>).

HIGH PERFORMANCE COMPUTING

High performance computing has now entered the Exascale era with Frontier at the Oak Ridge Leadership Computing Facility (OLCF) clocking in at 1.1 Exaflops--and at a cost not far from that of the newly commissioned FRIB. The ever-increasing computational power over the last decade has accelerated scientific discovery and transformed the field of low-energy nuclear physics and astrophysics. We are now entering a new and exciting era where we will see significant improvements in the simulation capabilities of atomic nuclei and nuclear matter, and their reactions with neutrinos and electrons, and stellar explosions. Results obtained by combining HPC with new methods will advance our understanding of nuclear phenomena by targeting predictive capabilities in the structure and reactions of light nuclei and few-nucleon systems; precision calculations of nuclear matrix elements for fundamental symmetries; neutrino and electron interactions in nuclei; properties of nuclei and nuclear matter; properties of fission such as mass and charge yields, excitation energy sharing between fragments, and total kinetic energy released; and detailed models of the sites of nucleosynthesis. These results will be relevant to many applications in nuclear energy, nuclear

security, and nuclear astrophysics. We will be able to provide predictions for key nuclei relevant to ATLAS, FRIB and other experimental activities worldwide, and guide state-of-the-art updates to evaluated nuclear data libraries.

There are several computing architectures at Exascale, driven by novel hardware components. Investments in HPC computing hardware should be matched by the scientific community's investment in people effectively using these computational opportunities. This can be done by strengthening collaborations between applied mathematicians, computer scientists, and nuclear physicists to design algorithms and refactor and optimize codes for these HPC computing resources (e.g., the migration of existing codes to graphics processing units, or GPUs).

Even as the high-end machines push the boundaries of computational capabilities, not all problems will require Exascale computing; the nuclear science community will still have significant use for 'capacity computing' at mid-sized machines, such as those part of the ACCESS network supported by the NSF. Such machines can be invaluable for, e.g., systematic parameter studies and uncertainty quantification, among many other goals.

We will need to articulate 'best practices' for data and code management within an emerging heterogeneous infrastructure of resources that connects facilities and academic institutions to decentralized storage architectures and federated and industrial computing clusters. It will be necessary to compose nuclear workflows from existing workloads and data deployed across multiple organizations to deliver developer productivity and performance portability in this internet of computing resources.

As making progress in our field becomes more and more dependent on access to computing resources, our need for computing hours will grow, and it is important that we have increased access to HPC platforms to enable the discovery of new science over the next decade. It is equally important that we support the nuclear community user base; train current and future nuclear physicists in 'best practices' and using HPC resources efficiently; and provide career pathways for computational scientists who straddle nuclear science and computer science.

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Artificial intelligence is the simulation of human-like behaviors by computers as expressed in processes such as problem solving, prediction, generative modeling, and decision making. Machine learning is a core subfield of AI in which algorithms are designed to build models from existing data that generalize to unseen data. This is converse to a traditional approach of fitting a pre-defined model to available data.

The availability of accessible ML tools and computational resources such as many-core co-processors have enabled the widespread use of ML across all avenues of society in recent years. There was no mention of AI/ML in the 2015 NSAC Long Range Plan, and the rapid growth of AI/ML in nuclear science has occurred only in the past few years.

Low-energy nuclear physics has seen ML employed in modeling, data analysis, experimental design, and operations. AI applied to large sets of experimental data allows for the automated classification of events of interest for nuclear astrophysics. Theorists working in nuclear structure, reactions, and astrophysics are using ML to improve and perform extrapolations of theoretical predictions and using statistical approaches such as Bayesian ML to perform uncertainty quantification. ML is being combined with model order reduction methods to produce fast and accurate emulators of otherwise computationally intensive calculations. Such emulators allow for efficient collaboration between theory and experiment and can be used to design new experiments with optimal sensitivity to the subject of interest.

ML is being used extensively in low-energy experiments for tasks such as detector design, determining backgrounds, and particle identification. AI/ML methods are being developed for use at accelerator facilities for efficient beam

tuning, optimal parameter settings, and operational safety. This is useful not only for current operations but also for the planning of future upgrades and new facilities. In low-energy nuclear physics, many different detection methods are used across many experimental setups. This ‘multi-messenger’ environment leads to uniquely structured data and analysis methods. Looking forward, developing machine learning models that interact with such non-traditional data structures is an area of active and early-stage research in AI. Nuclear data efforts towards standardized, easy-to access databases will enable the use of ML on aggregate data.

With the widespread use and potential of artificial intelligence in nuclear physics, broad education efforts will ensure that all nuclear scientists have access to the foundations of AI literacy, providing the ability to identify potential uses of AI and interact with trained machine learning models. Interdisciplinary efforts with AI scientists will allow the rapidly advancing field of AI to develop in directions that also push nuclear science forward.

Looking at recent disrupting technology that arose from AI, such as large transformer models, impacts could be realized in nuclear physics with community standards that enable training large models. Large models are typically trained on massive amounts of data. These standards include sharing data in a manner that is interpretable across research groups and sub-disciplines in nuclear physics and publishing well-documented and maintained open-access code. Importantly, training large models requires significant many-core computational resources, such as GPUs and tensor processing units. Access to such resources will be essential to push forward large-scale ML efforts in nuclear physics. Looking towards the next ten years of AI/ML in nuclear physics, attention towards trustworthy deployment of models and well-maintained software will ensure the realization of the potential that has been demonstrated in recent years. Additionally, creating opportunities for nuclear science to play a collaborative role in active AI research will allow the research to evolve in directions that will advance both fields.

QUANTUM COMPUTING

The rise of quantum computing may present us with the most significant leap in computational power since the advent of silicon transistors. Potentially far eclipsing the gains we have seen in the past decade at HPC arising graphics processing units and machine intelligence, quantum computing holds the promise for exponential advantages for many classes of problems. These computers, built from controllable quantum systems, take advantage of quantum mechanical phenomena such as superposition, interference, and entanglement to enable a computational space that grows exponentially with this size of the computer and can act simultaneously on the complete state of the device. As entangled quantum systems, quantum computers are ideal platforms for modeling the complex properties and physics of atomic nuclei and other quantum many-body systems. There was no mention of quantum computing in the 2015 NSAC Long Range Plan, and the growth of quantum computing in nuclear science, much like most domain applications, has occurred in only the past few years.

There has been much focus in the press about achieving quantum supremacy or quantum advantage, where a quantum device can solve a problem faster than any existing classical computer. In nuclear physics, however, the objective is to solve important scientific problems where classical computing approaches have known deficiencies. One large class of such problems is the nuclear many-body problem. While classical computing has achieved many important milestones in the nuclear many-body problem, some topics have remained elusive such as the properties of dense nuclear matter, non-equilibrium dynamics, and the spectral density of states. For these important problems, quantum computing has the potential to make a significant impact. In the past few years, some work has been done in developing quantum algorithms for eigenstate preparation, time evolution, and spectral density calculations. These studies have been demonstrated on quantum devices built and maintained by companies such IBM, Rigetti, Google, Quantinuum, IonQ, etc., as well as testbed programs at several DOE national laboratories.

These devices use various technologies such as superconducting qubits and qudits and trapped ions. To address problems at the forefront of nuclear physics, however, all devices will need significantly more qubits and will need significantly lower error rates and longer decoherence times.

With the first quantum simulations just coming into reach now, the next decade will be formative in setting the shape of quantum computing, from the form these platforms assume to their access models and scientific accessibility. By engaging now, the nuclear science community can lead the development of quantum applications and guide the design of quantum platforms just as it has with classical high-performance computing. This leadership will ensure that future platforms are well suited to advancing nuclear science and our understanding of the fundamental properties of visible matter.

8 BROADER IMPACTS OF NUCLEAR STRUCTURE, REACTIONS, AND NUCLEAR ASTROPHYSICS AND ACCELERATOR SCIENCE

INTRODUCTION

Beyond the advancement of our basic understanding of nature, nuclear science also makes direct and major contributions to solving societal problems and improving the US economy. These contributions include sensitive new tools to detect environmental hazards, such as PFAS contaminants, and the testing of critical electronics for space-based applications. The technology and techniques of nuclear science advance nuclear medicine toward diagnoses and cures for a wide range of diseases. These also help us determine how to respond to nuclear threats and to the spread of nuclear materials. Equally important, the related accelerator science effort is a multi-hundred-billion-dollar enterprise at the core of many industries in the U.S., central to the health industry and to future efforts to meet our national energy needs in an environmentally sound way [Afa22]. Moreover, the field of nuclear science provides the primary educational pathway to our core expertise in nuclear detector technologies, data analysis and data science techniques, accelerator science, and cryogenic engineering. This highly trained workforce helps ensure continued growth in both U.S. industry and medicine.

The information compiled here is the result of many contributions to the Fall 2022 town meeting. This session included 5 invited talks and 28 shorter contributed presentations. These spanned a broad range of major advances in the areas of nuclear science, applications, and accelerator science. These contributions are summarized below. Significant, recent achievements in the field were noted, including the successful commissioning of FRIB, the demonstration of the use of liquid lithium stripper technology, multiple charge state acceleration, multi-user operation at ATLAS, 3D imaging of radiation in real environments, the expansion of heavy-ion electronics testing capabilities, and development of techniques to observe environmental contaminants.

To continue progress, challenges that must be addressed by the field were identified by the participants. Addressing these challenges is essential to further the underlying nuclear science and to continue to make significant societal contributions. Overarching challenges identified in nuclear science applications include:

- Sufficient heavy-ion facilities capability for single-event upset chip testing for space applications.
- The need for new detector technologies for medical and homeland security applications.
- Sufficient accelerator resources and facilities for rapid environmental testing.
- Expanding machine learning and artificial intelligence to address complex issues more efficiently.

The overarching challenges identified in accelerator physics include:

- Advancing key technologies in superconducting radiofrequency (SRF), ion sources, and magnets.
- Transformation technique for low-beta SRF to dramatically reduce size and cost.
- Transfer of technology and expertise for facilities and applications.
- Development of industrial partners for delivery of advanced components (e.g. [SNO22]).
- Meeting the needs of the applied users for accelerator technology and generated data.
- Advancing nuclear techniques for homeland security and medical applications.
- Application of ML and AI to improve operations at current and future nuclear facilities.

DOE SC NATIONAL USER FACILITIES AND BROADER ACCELERATOR SCIENCE RESOURCES

Major facilities that contribute to this important enterprise are the DOE SC user facilities at Argonne National Laboratory (ATLAS) and Michigan State University (Facility for Rare Isotope Beams, FRIB). The DOE SC NP Centers of Excellence and the broader ARUNA network of laboratories [Aru22] are a vital source making essential contributions.

A major achievement discussed in this session was the completion of the Facility for Rare Isotope Beams (FRIB) project. Completion was accomplished on time and on budget. FRIB will be able to produce beams of nearly 80% of all the predicted isotopes of elements up to uranium. The FRIB LINAC consists of 324 superconducting cavities in 46 cryomodules. The FRIB cryomodules were completed at a rate of more than one per month and together comprise the world's highest energy heavy ion LINAC. At the full power of 400 kW it will be the world's highest power facility for making rare isotopes. A key new technology of the FRIB accelerator is the use of a film of liquid lithium for charge stripping [Kan22]. This is illustrated in Figure 8.1 where the right side diagrammatically illustrates the film, and the left side shows an image of the system in operation.

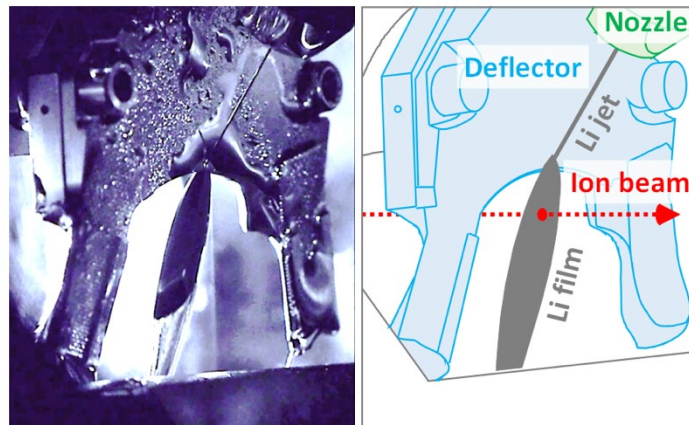


Figure 8.1: Liquid lithium stripper foil at FRIB. Left, image; Right, diagram illustrating the beam position on the foil.

A key capability of FRIB is the simultaneous acceleration of multiple charge states in the LINAC and the delivery of those beams to the production target with sub-millimeter precision [Ost21]. FRIB began operation in May 2022 and multiple experiments have been completed. First scientific results were published during the Town Meeting [Cra22]. Key future developments include implementation of AI/ML and control of beam halo both to facilitate 400 kW operation. A major initiative critical to realize new scientific opportunities is the upgrade of the FRIB energy to 400 MeV/u (FRIB400). Key technology developments continue at FRIB, including improvements in diagnostics and heavy ion detectors that allow ion-by-ion identification at high rates.

The ATLAS national user facility at Argonne is the DOE stable beam facility for nuclear physics. It is positioned to support the physics of the low-energy community via major initiatives such as the Multi-user Upgrade, nuCARIBU, and improvements to enable high-intensity stable beams for a future N=126 factory. Future compact, low-power single-cavity or multi-cavity cryomodules based on next generation SRF technologies will provide transformationally better performance and flexibility. Other operational improvements include low-energy bunching of high-intensity beams, re-bunching of in-flight beams, and energy adjustment for Area 2 experiments as part of multi-user operation. Near-term developments include:

- Targetry developments that are needed for nuCARIBU flexibility and improved in-flight production.
- Coordinated helium conservation and recovery efforts to ensure sustainable accelerator operations.
- Development of Nb₃Sn cavities for low-beta ion LINACs.

Modern accelerating structures at ATLAS assembled in ultra-clean environments also drive the need to maintain these clean systems and to develop and improve upon techniques to mitigate performance degradation and support reliable operation at ATLAS and all other current and future NP accelerator facilities.

Both ATLAS and FRIB use and, at the same time, require advances in ECR ion source technology. ATLAS is developing a third-generation superconducting source, but these are complex and costly. An 18 GHz room-temperature or hybrid (RT & SC) source may reduce costs and operational complexity and can provide the required beam intensities for most species. A comprehensive design study of an 18 GHz ECR source is underway which accommodates the introduction of solid materials. A cost and workforce profile will be developed. A goal is early engagement of U.S. vendors to develop competitive pricing. At FRIB a 4th generation 28 GHz source is under development in collaboration with Lawrence Berkeley National Laboratory. Current ion source performance continues to improve driven primarily by increasing the excitation frequency of the ECR plasma. Generally, the best performance obtained today is accomplished with superconducting ECR ion sources operating at 28 GHz. Beam commissioning with the FRIB 28 GHz ECR has begun. The next generation of ECR ion sources operating above 28 GHz will face many new challenges, in particular with the superconducting magnets and cryogenic heat load requirements, as well as with the plasma chamber cooling and X-ray generation. Continued advances here will be key for future accelerators and applications.

TECHNOLOGIES AT THE INTERSECTION OF NUCLEAR SCIENCE, ACCELERATORS AND APPLICATIONS

Specialty, superconducting magnets for research and applications require enhancements to move beyond the current iron-core quadrupole nested with multipoles. The multipoles induce a dipole field component generated during sextupole excitation. Optics optimization with extra tools are required to simulate these effects. The goal is to move towards more efficient “iron-free” coil-dominated quadrupole magnets. These magnets could have excellent field quality allowing for more efficient beam separation and purification. Current-dominated fields would enable easy beam tuning and these magnets would be comparatively compact and lightweight. Global activities in this area include DCT quad developed S3 at GANIL, France, CCT/DCT development on-going by HFRS at HIAF, China, CCT dipole at HL-LHC, CERN, and with increasing frequency, several industrial participants.

Scientists at the university-based ARUNA laboratories pursue independent research programs in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications, which build bridges to other research communities. Their efforts include study of radiation effects by measurement of the response of space-based electronics here on earth, development and use of analytical techniques (Material Analysis) such as Particle Induced X-ray Emission (PIXE), Particle Induced Gamma-ray Emission (PIGE), Rutherford Back Scattering (RBS), neutron beams analysis, neutron-induced cross-section measurements, neutron capture analysis, and detector development. The ARUNA labs have significantly more flexible running schedules than the larger user facilities, allowing rapid investigation and study of new ideas.

A key area in the application of nuclear technology is radiation detection and imaging at the intersection of nuclear science and engineering, security, health, and society. The nuclear techniques in radiation detection and analysis can be applied to the needs of nuclear security (threat detection, safeguards, and nuclear forensics), nuclear

engineering (reactor and fuel monitoring), radiation protection (facility monitoring, decontamination, decommissioning, remediation, emergency response, consequence management) and nuclear medicine (disease processes, cancer diagnosis, and therapy). As in the case of accelerator science, the workforce educated in these techniques are in themselves a vital national resource. Our community has demonstrated the application of these technologies, as well as adaptations to many specific challenges. Positively impacted agencies include DHS, NNSA, DTRA, DARPA, NIH, DOE SC, and others.

Key technological developments discussed here include improved germanium detectors, strip detectors and point contact detectors, for precise and sensitive gamma ray measurements that allow source localization. New technologies that offer extremely fast timing for medical application or upscaling to large detectors used for reactor monitoring have also been made. These developments allow fast 3D images of radiation in the environment as shown in Figure 8.2 [Vet19].

Improvements in radiation detection also enable realization of the full benefit of new nuclear medical isotopes. Advances in radiation cancer therapy utilizing high Linear Energy Transfer (LET) and high Relative Biological Effectiveness (RBE) promise higher efficacy in cancer treatments, since they can provide a well-localized and effective treatment e.g., Targeted Alpha particle Therapy (TAT) and external Ion Beam Cancer Therapy (IBCT). The key is to ensure that the treatment is well localized within the cancer sparing the healthy tissue. Conventional gamma-ray imaging modalities are insufficient in realizing the full potential since they require gamma-ray imaging capabilities over a broad range of energies. New detector technologies are addressing these needs.

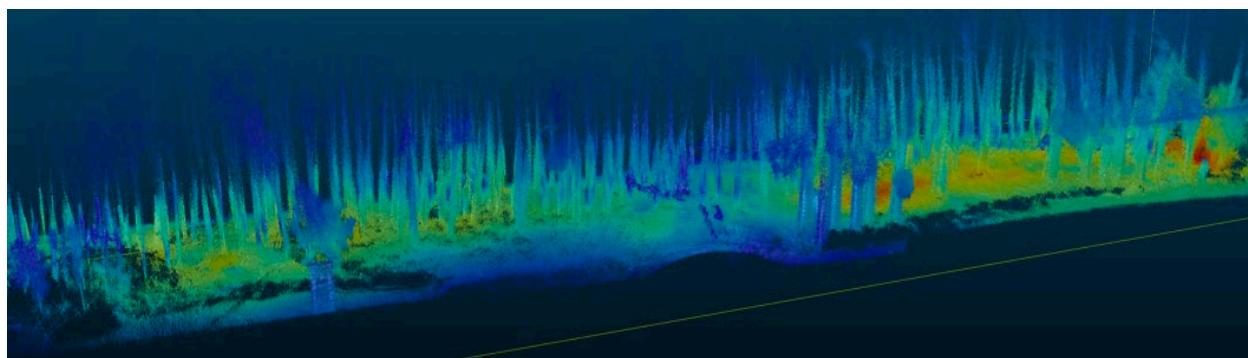


Figure 8.2: Image of ^{137}Cs radiation in a bamboo forest (trees can be seen in the image) near Fukushima, Japan. New LBNL 3D “mapping” radiation device. Brighter color indicates more ^{137}Cs . The image is a 15-min measurement and reconstruction with digital removal of houses. (Credit: Berkeley Lab)

Though radiation is a natural component of our environment, in space the radiation environment is more extreme, lacking the protection of the atmosphere and Earth’s magnetic fields to shield us from the cosmic rays. These include lighter and heavier ions of several hundred MeV/nucleon. The radiation (whether natural or reactor- or accelerator-produced) can have a significant impact on the reliability of electronics by introducing ‘single-event upsets’. These have serious implications for aerospace and defense, autonomous automotive vehicles, implantable medical devices, server farms and critical infrastructure, and accelerator instrumentation. Low-energy nuclear science facilities provide most of the testing infrastructure to explore these issues and validate electronics for critical applications, such as space flight and avionics. The importance of this issue to our nation was highlighted in two recent high-level reports, one from the National Academies, *Testing at the Speed of Light* [NAS18], and one from the Executive Branch, *National Space Weather Action Plan* [EXB19]. These reports highlight the growing use of, decreasing supply of, and increasing strain on accelerator infrastructure available for testing. There are indications

of an aging workforce in a domain that requires specialized training and skills. The primary facilities that the nation relies on for this work are the TAMU cyclotrons, the LBL 88-inch cyclotron, the FRIB accelerators, and to some extent the BNL NSRL facilities. Present testing capacity is 4,500 hours per year with an estimated demand of more than 12,000 hours per year. Investments will add another 5,000 hours, but the demand is predicted continue to grow. The TAMU Radiation Effects Facility maintains two dedicated beamlines, alone delivering over 4000 hours per year for testing with light and heavy ions. Workforce in this area is another critical contribution that low-energy nuclear physics makes with supported university educational programs in radiation effects at Michigan State, Vanderbilt, UT Chattanooga, Stony Brook, Purdue, Georgia Tech, ASU, Brigham Young, and Washington University at St. Louis.

Work at Notre Dame University's St. Andre Facility has developed practical applications of Proton Induced Gamma-ray Emission (PIGE) spectroscopy, a technique that allow sensitive probes for environmental contaminants such as PFAS observed in common consumer products such as cosmetics [Whi21] and school uniforms [Xie22]. PFAS and other carcinogens have now been identified in many consumer products. The PIGE technique is used to detect trace amounts with a few minutes of analysis. Similar analyses are performed at Hope College where they have widely used instrumentation for PIXE (in-air), RBS, PIGE (in-air), IBIL, and NRA. Notre Dame has lowered detection limits for aqueous PIGE measurements [Tig21] to help screen for PFAS in drinking water supplies. Hope College is developing inexpensive fast-plastic Compton suppressors and improved sample preparation techniques to lower level of detection as well. These programs also provide data for space flight by sample irradiation, for example irradiation of mice with protons or neutrons. They similarly perform irradiations of novel photovoltaics (for radiation resistance studies in space environments) and development of new superconductors (changes with lattice damage).

Union College has an emphasis on IBA of environmental samples. Examples of measurements include PIXE Analysis of Synthetic Turf [Tur18], Pb measured in crumb rubber in fill samples at levels above health-based soil standards. They have found high concentrations of bromine in fill samples most likely due to brominated flame-retardants. The distribution and relative concentrations of elements in blade samples indicative of metal-oxide pigments used to color the blades has been studied. The Edwards Accelerator Laboratory at Ohio University performs neutron-induced reactions and related analyses. UMass Lowell accelerator and research reactor facilities are used for several applied studies including neutron damage of components. They also do advanced detector development and demonstration.

Nuclear science programs using the DOE-SC user facilities and the ARUNA accelerator facilities provide critical data for applications. One example is surrogate reactions that can be used to determine neutron capture rates on unstable nuclei. A surrogate reaction is chosen that forms the "same" compound nucleus as the desired reaction. Measuring the decay of the compound nucleus as a function of excitation energy provides constraints on Hauser-Feshbach parameters that are used to calculate the desired reaction. This means that the surrogate reactions can provide constraints on quantities calculated by or input into Hauser-Feshbach codes (cross sections, gamma strength functions, nuclear level densities, etc.) Indirect techniques such as surrogate reactions provide essential constraints on neutron-induced reactions relevant to applications, including Stockpile Stewardship. New opportunities for surrogate reactions on rare-isotope beams would be enabled by the ISLA recoil separator at FRIB with ReA beam energies exceeding 10 MeV/nucleon.

TRAINING THE U.S. WORK FORCE

As referenced repeatedly in these discussions, one of the key contributions of the nuclear science accelerator and technology program is the development of a highly trained workforce. The ARUNA laboratories are responsible for hands-on training of graduate students at the forefront of experimental and theoretical nuclear science. The Accelerator Science Education and Training program at FRIB currently has 26 students enrolled, with two PhD

students who graduated this academic year and two PhD students that are expected to graduate in Spring 2023. This program supports internships at national laboratories to develop accelerator expertise. This summer, eight ASET students are funded for a summer internship at National Laboratories. Eight ASET students are also stationed at national laboratories for their thesis research. A certificate-based Master's program in accelerator science and engineering was established in the Physics and Astronomy Department at Michigan State University as part of this initiative. Another initiative is the MSU Cryogenic Initiative. This program educates and trains future cryogenic engineers and system innovators, investigates, proposes, and fosters efficient cryogenic process designs, performs research to advance cryogenic technologies, and sustains a knowledge base of cryogenic technology and skills. The demand for workforce in this area is high and this represents a unique contribution of the nuclear physics program.

SUMMARY

These pages document the significant progress and broad national impact over the past decade of accelerator and nuclear science and the equally significant contributions this science has made by applications of the technology to solving societal problems. The impact is direct, immediate, and is increasingly so over time. Accelerator science and technical developments in our field bears directly on efforts to secure our nation's defense, identify environmental hazards, generate the isotopes and beams needed for a healthy nation, and to provide the data and verification for multiple U.S. industries. Improvements in all these areas and realization of new benefits depends on a future well-trained workforce, which current and planned facilities and programs also provide. These immediate, wide-ranging, and powerful benefits argue for continued broad support for the core activities at DOE Office of Science NP supported facilities.

BIBLIOGRAPHY

[Afa22] <http://www.acceleratorsamerica.org/>

[Aru22] ARUNA: Advancing Science, Educating Scientists, Delivering for Society, [Nuclear Physics News 31, 4 \(2022\)](#).

[Cra22] H. L. Crawford *et al.*, Phys. Rev. Lett. 129, 212501 (2022).

[EXB19] US Office of Science and Technology Policy, [National Space Weather Strategy and Action Plan](#) published: April 05, 2019.

[Kam22] T. Kanemura *et al.*, Phys. Rev. Lett. 128, 212301 (2022).

[NAS18] National Academies of Sciences, Engineering, and Medicine. 2018. [Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure](#). Washington, DC: The National Academies Press.

[Ost21] P. Ostroumov *et al.*, Phys. Rev. Lett. 126, 114801 (2021).

[SNO22] Snowmass 2022, Community Frontier, Applications and industry topical group, [Nurturing the Industrial Accelerator Technology Base in the US](#).

[Tig21] M. Tighe *et al.*, ACS ES&T Water 1, 2477 (2021).

[Tur18] M. F. Vineyard *et al.*, Environment and Ecology Res. 6(1), 60 (2018).

[Vet19] K. Vetter *et al.*, Sensors 19, 2541 (2019).

[Whi21] H. Whitehead *et al.*, Environ. Sci. Technol. Lett 8, 538 (2021).

[Xia22] C. Xia *et al.*, Env. Sci. Tech. 56, 13845 (2022).

9 NUCLEAR DATA

Community contributions emphasized the essential role nuclear data plays in all facets of nuclear science. We highlight the four main principles required of nuclear data in order to meet the needs of the basic and applied nuclear science communities [Ber22, Kol22, Kon17]: reliable and credible – data must be correctly evaluated; up to date – results from all measurements should be promptly incorporated; comprehensive – all measured quantities and their uncertainties need to be included; and accessible – data should be made available in modern and interoperable formats.

The collaborative efforts of the worldwide community of experimentalists, theorists, evaluators provide nuclear data for basic nuclear physics and applied nuclear technology research. Within the United States, the U.S. Nuclear Data Program (USNDP) is tasked with the responsibility to collect, evaluate, and disseminate these nuclear physics data for basic nuclear physics and applied nuclear technology research. The USNDP network is supported by the DOE Office of Science, Office of Nuclear Physics (DOE/SC/NP) funding and comprises nuclear data experts from national laboratories and academia across the United States. The focal point of the network is the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory, which is the major outlet for storing and disseminating nuclear data in the U.S. The mission of the USNDP is “to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. USNDP also addresses gaps in the data, through targeted experimental studies and the use of theoretical models.” By carrying out this mission over the next decade, the USNDP network will continue to develop and maintain key components that motivate basic science discovery and support the progress of advanced applications.

It is imperative to maintain an effective US role in the stewardship of nuclear data. There is a continuous U.S. commitment to the international nuclear data networks, which are coordinated primarily by the International Atomic Energy Agency in Vienna (IAEA) and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA-OECD) in Paris. A critical issue is to maintain a high level of expertise in nuclear data evaluation to assure sufficient breadth and quality of the nuclear databases and to meet the requirements of a continuously developing user community. Domestically, DOE/SC/NP oversaw the creation of the Nuclear Data Interagency Working Group, a network of program managers from federal agencies including DOE/SC/NP and NNSA, the NRC, etc., who meet regularly to coordinate a response to initiatives brought forward at the annual Workshop for Applied Nuclear Data Activities (WANDA), see [Ber22]. There will be increased interagency-supported crosscutting opportunities for nuclear data that enrich the utility of nuclear data in both science and society.

Presentations throughout the nuclear data sessions echoed a high demand for reliable, complete, and up-to-date evaluated nuclear structure and reaction data to enable efficient progress in active research programs; there was an emphasis on the importance of new measurements being made available in nuclear data libraries as rapidly as possible. This highlights the crucial role nuclear data plays in the scientific advancement of the fundamental nuclear physics research enterprise. The availability of credible and reliable nuclear data libraries provides a bridge between science, technology, and society by making the results of basic nuclear physics research available to a broad audience of users. Examples were given on the implementation of nuclear science and nuclear data that enabled the successes of applied missions in the areas of defense and security, nuclear energy, space exploration, isotope production, and nuclear medicine diagnostics and treatments. The keynote presentation on nuclear applications highlighted the importance of nuclear data libraries and demonstrated their profound socioeconomic impact enabled through applications of modern nuclear science.

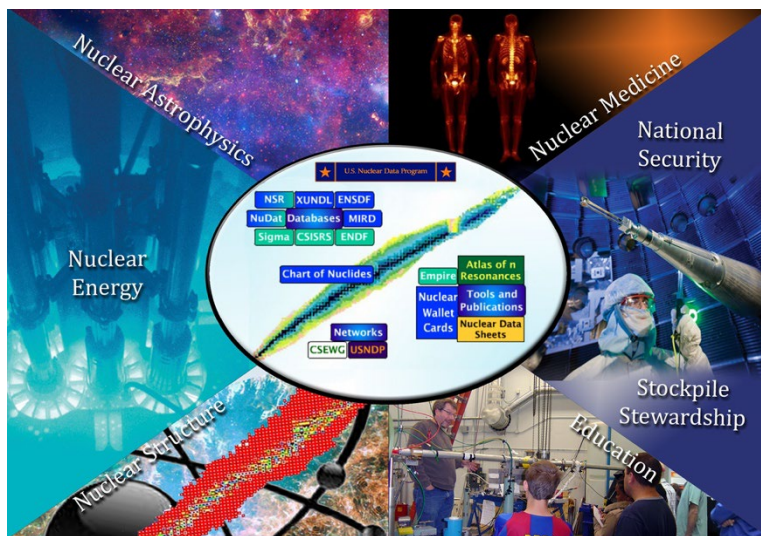


Figure 9.1: The core USNDP nuclear physics databases and products, and their main areas of impact for science and technology.

Looking forward to the next decade of discovery opportunities provided by FRIB, ATLAS and the ARUNA laboratories, the availability of reliable and up-to-date nuclear data is essential to develop and test new theories of atomic nuclei, to aid in planning of illuminating experiments, to provide optimal input for astrophysical simulations and to enhance the use of isotopes in society. To best enable the most effective utilization of the nuclear data libraries, the community cannot wait 10-20 years for the data to appear in the major evaluated nuclear data libraries, which is the current average update cycle. Rather, to allow the community to take full advantage of the significant investment in experimental facilities and devices, the evaluation times should be on the order of a few years or less. Up-to-date databases are imperative and can be achieved through development of effective analysis tools that improve evaluation efficiency, by continuous support for the existing data evaluation efforts and by an expansion of the pool of skilled nuclear data evaluators.

Within the USNDP, initial steps to modernize database formats and infrastructure are being made for both the Evaluated Nuclear Data File (ENDF) and Evaluated Nuclear Structure Data File (ENSDF) database structures; new hierarchical and object-oriented program friendly formats are being designed. These developments open the possibility for automation via modern artificial intelligence and enabling discovery science through machine learning methods. Continued investment into modern hierarchical, object-oriented nuclear data formats and associated APIs are necessary to develop a compilation, evaluation and dissemination platform which can make full advantage of these methods. Such a system would enhance data accessibility and usability, allow new and seamless connections between databases, and provide new capabilities to store a broader range and type of data.

The field must address the President’s “Memorandum on Increasing Access to the Results of Federally Funded Research” [Nel22]. An open discussion on the legitimacy of present data management plans is necessary to guide future infrastructure needs required to meet federal compliance expectations. Most current plans are focused on access to filtered and refined nuclear data that are published in journals, conference proceedings, lab reports or other media. These processed results, however, generally make up just a small fraction of the data that were collected and do not capture the full breadth of the analysis, such as calibrations, simulations, and analysis routines. This limited view makes validation of results and verifiability of experiments, which are the bedrock of the scientific method, challenging if not impossible. Resources to support fulfilment of this mandate may be required at a

combination of local and national levels. Support for scientific, computational, and administrative efforts will be essential to enable any practical repository for open access data. The Human Genome Project, the CERN Open Data portal and the MAST astronomical data archive are examples of successful centralized data preservation and data sharing programs, but the broad diversity in custom developed or proprietary software utilized in the vast nuclear physics enterprise create the need for a more complex solution.

NUCLEAR STRUCTURE



Figure 9.2: The cycle of nuclear physics research.

ENSDF is the definitive, worldwide resource for nuclear structure data. It forms the cornerstone of low-energy fundamental nuclear physics and nuclear astrophysics while providing vital input in various medical, non-proliferation, homeland security, and industrial applications. ENSDF contains all discrete, experimental nuclear structure and decay data covering more than 100 years of measurements on the entire chart of nuclei. The path from published experimental data to a final ENSDF evaluation is an intricate process that considers all measurements of a particular quantity with physics-based codes, theoretical models, and systematic surveys to provide users with recommended values for nearly every discrete property of each nucleus that has been studied in the laboratory. A companion database to ENSDF is XUNDL (eXperimental Unevaluated Nuclear Data List) which contains a critical compilation of recent papers in experimental nuclear structure datasets. XUNDL is composed of data that correspond to a single journal article, and are compiled in the same format as ENSDF, helping to streamline the incorporation of data into ENSDF at a later stage. The bibliographical Nuclear Science Reference (NSR) library is also of vital importance to the ENSDF evaluation effort. For perspective on the world-wide use of ENSDF, the graphical interface to the database, NuDat, exceeds more than 3.5 million database retrievals per year through the NNDC website.

There is a rapidly growing body of new experimental data that is produced at the experimental nuclear physics facilities around the world that needs to be incorporated into ENSDF to influence major science questions to the full advantage of the community. ENSDF is also used to benchmark sophisticated theoretical models, in systematic studies to uncover new structure phenomena, and to investigate various nucleosynthesis processes. On the applied side, ENSDF is essential for the production and use of radioisotopes in nuclear medicine, defense, and security, as well as in other applied areas such as diagnostics for inertial confinement fusion (ICF), whose importance has been magnified by the December 2022 announcement of ignition at the National Ignition Facility (LLNL). However, the age

of ENSDF, measured as the time between the latest evaluation and the present, is growing and it is approximately 10 years on average. Up-to-date databases was voiced as the main nuclear data need throughout the contributions and subsequent discussions. Sustained support of the current nuclear data evaluator network is essential to maintain the databases at their current level. New AI/ML techniques should be explored to facilitate a streamlining of the evaluation process; however, computational techniques alone will not solve the issue of the aging databases. An expansion of the pool of skilled nuclear data evaluators is imperative to meet database currency needs and to allow for the incorporation of new quantities into the database.

The legacy database format, such as the fixed-field, 80 column one, places serious limitations on the types of data which can be stored in the file, as well as the precision to which data can be reported. Changing experimental trends and new experimental capabilities demand an expansion of the current database. For example, there was much discussion on the need to incorporate quasi-continuum data, such as radiative strength functions and level densities. While these quantities can reside in ENSDF, they will find significant overlap and use in the nuclear reaction libraries. Additional continuum quantities of interest include beta-delayed neutron spectra and Total Absorption Spectroscopy measurements. Adding these quantities to the new ENSDF format is a planned activity. However, no defined procedures for evaluating these quantities nor people with domain specific expertise to perform these evaluations currently exist. Providing necessary training to the pool of nuclear data evaluators to accommodate such needs is also important.

NUCLEAR REACTIONS

Nuclear reactions are an integral part of basic nuclear science and its applications. Reactions can be used as probes to understand the structure of nuclei, and to study the forces that drive the interactions between them. Accurate knowledge of nuclear reaction cross sections is essential to produce radioisotopes for medical use, for nuclear security, fusion and fission energy applications, beam-induced therapy, astrophysics and more. Commonly used reactions are induced by protons, deuterons, and alpha capture, as well as all types of neutron-induced reactions, including fission. For many applications, the need for nuclear reaction data goes far beyond the need for a single reaction cross section. Often one needs to use complex reaction networks that include thousands of reactions, and their cross sections need to be known with high accuracy. For this reason, nuclear reaction data need to be available for such applications in a consistent and practical manner.

Experimental (mostly neutron-induced) reaction data are compiled into the EXFOR library by the international Nuclear Reaction Data Network, coordinated by the IAEA. It is merged with the latest reaction theories by the Cross Section Evaluation Working Group (CSEWG), a collaboration between basic science who makes data and applied customers who use it, to produce the comprehensive ENDF evaluated reactions library. The successful use of ENDF in applications for the next decade will depend on the continuous integration of new experimental measurements supplemented by the most appropriate theoretical models. Nuclear reaction cross sections are characterized by non-resonant, resonant, and statistical components. Different nuclear data is needed to understand each of these terms. Non-resonant cross sections often rely on the properties (energy, width, spin/parity, single particle nature) of levels lying below a reaction threshold; this component often dominates at low reaction energies. Resonant contributions rely on the energy, partial and total widths, and spin/parity of levels above the threshold, and in some cases give contributions many orders of magnitude larger than non-resonant terms. At higher energies when resonances overlap, a statistical (Hauser-Feshbach) approach is needed wherein properties such as level densities and photon strength functions must be averaged over many resonances. Interferences between resonances (in the resonant term) and between these terms complicates the description of certain reactions, as well as unusual effects like pygmy resonances, clustering, and doorway (multi-step) states. Theoretical descriptions play an essential role both



Figure 9.3: LENZ spectrometer at LANL.

in understanding reaction mechanisms and in extracting nuclear structure information from reaction measurements. The availability of up-to-date reaction information is essential to improve *ab initio*, microscopic, coupled-channels, statistical, and other reaction models.

Evaluations of nuclear reaction data are critical for providing the community with accurate information. Many tools and libraries for tracking nuclear reaction properties are already available. In some cases, new measurements, particularly those involving unstable isotopes and/or indirect methods do not have a home in the nuclear data framework. This is a need that the community will need to address.

Direct nuclear reaction cross section measurements take place at a broad range of facilities. This includes stable beam facilities such as ATLAS and the ARUNA laboratories, neutron facilities, underground laboratories, gamma-beam facilities and of course FRIB for radioactive beam experiments. Some new developments include the combination of advanced instrumentation with radioisotope production which opens the door for new cross section measurements on long-lived radioisotopes. The intense radioactive beams offered at FRIB, combined with the development of new equipment, enable new cross section measurements as well.

On top of the direct measurements there has been significant effort in developing indirect techniques to constrain experimentally nuclear reactions when a direct measurement is not possible. This involves the extraction of nuclear level information to inform resonance calculations, and more recently capture reactions on short-lived isotopes. Three main techniques have been developed for the latter: the surrogate method [Esc18, Rat19], the β -Oslo method [Spy14] and the Shape Method [Wie21]. These are complementary approaches and provide strong constraints to neutron-capture reaction cross sections. As part of the indirect techniques, a new data need emerges which involves the collection and evaluation of nuclear structure data in the statistical regime, such as nuclear level densities and photon strength functions [Kaw20].

Advances in computational methods, computing power, and machine learning techniques will enable several new developments. Uncertainty quantification of nuclear theory has been a major effort in both the prediction of nuclear reaction cross sections and to communicating estimates of data accuracy to users. In addition, Bayesian methods have been used for extrapolations into energy regions of interest where experimental data are not available. Finally,

there is a need for a greater focus on both experimental and evaluation reproducibility and data sharing. With the proper tools and community actions, this will enable automation and speed the integration of new results into libraries that serve users.

Overall nuclear reactions are needed for basic science and a broad range of applications and nuclear data availability is extremely important for this purpose. With new developments and new types of data the need to evolve emerges. New measurements, evaluations and nuclear theory calculations need to be available to the community in a consistent and practical way.

NUCLEAR ASTROPHYSICS

All properties of the atomic nucleus play a role in astrophysical phenomena, ranging from Big Bang nucleosynthesis to stellar evolution and explosions. The impact of a given nuclear property depends on the thermodynamic conditions of the environment. At elevated temperatures, beyond a billion kelvin, groups of nuclear reactions form reaction rate equilibria (quasi-statistical and nuclear statistical equilibrium). During equilibrium, the rates of such nuclear reactions have no impact on the nucleosynthesis, which instead depends sensitively on the masses of the nuclei involved.

In the absence of reaction rate equilibria, either because the temperature is too low or matter freezes out of equilibrium due to expansion, rates of individual reactions are essential to understanding the nucleosynthesis. If cross section data are available at the energies of interest, an experimental thermonuclear rate can be estimated by fitting the data using a suitable nuclear model (e.g., ab initio methods, microscopic theory). Significant progress was made in this regard since the 2015 Long Range Plan by developing Bayesian models for data fitting and uncertainty quantification [Zha15, Ili16]. When nucleosynthesis takes place at energies below the experimentally studied region, the low-energy S factor needs to be obtained by extrapolation using theory as a guide (e.g., R matrix). Additional low-energy resonance contributions to the total rate can be estimated from nuclear structure studies (e.g., transfer reactions, Trojan-Horse Method; see [Tri14]).

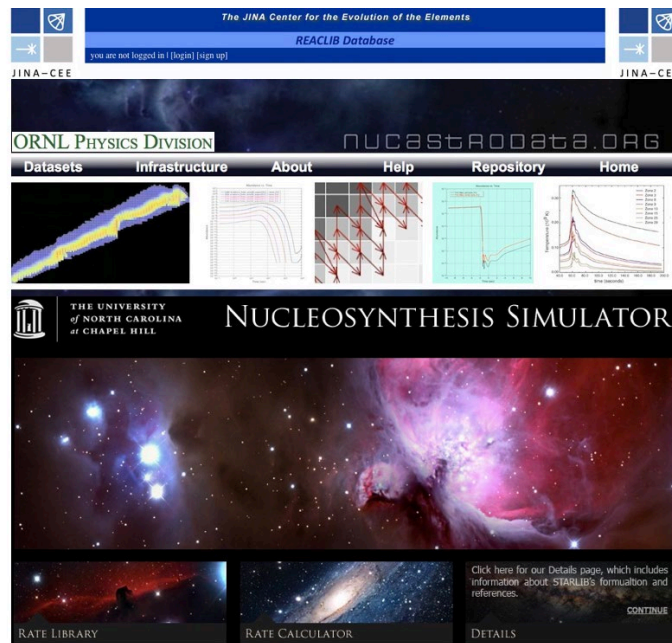


Figure 9.4: 1 Examples of nuclear reaction rate libraries.

Large nucleosynthesis reaction network simulations incorporate tens of thousands of different nuclear reactions involving nuclei located between the proton and neutron driplines. Among these reactions, nuclear reaction data are available for a small fraction only. For a large majority of reactions in such networks, the thermonuclear rate must be estimated using statistical nuclear theory (e.g., Hauser-Feshbach model). This requires knowledge of transmission coefficients, optical-model potentials, gamma-ray strength functions, and level densities. In the absence of direct cross section data, experimental techniques to constrain all these quantities exist, and have recently been extended to nuclei away from stability [Spy14, Esc18, Rat19, Wie21, Ahn19]. Hauser-Feshbach theory is also indispensable when laboratory thermonuclear rates need to be extrapolated to high energies, for estimating the effects of thermal nuclear excitations (stellar enhancement factors), or for calculating stellar reverse rates from the corresponding forward rates using partition functions [Rau00].

An experimental thermonuclear rate is typically estimated from: (i) reaction cross sections, resonance energies, strengths, and partial widths, measured in the reaction that takes place during the stellar burning at the relevant energies; (ii) excitation energies, spectroscopic factors, ANCs, spins, mean lifetimes, and branching ratios of important levels, measured by using suitable reactions other than the one taking part in the burning; and (iii) Hauser-Feshbach calculations. The required nuclear properties are compiled and evaluated under the U.S. Nuclear Data Program and transmitted to the community via a number of libraries (AME/NUBASE, ENSDF/XUNDL, ENDF/EXFOR, etc.). Based on this experimental nuclear reaction and structure information, the nuclear astrophysics community constructed and maintains several reaction rate libraries (e.g., REACLIB, BRUSLIB). These represent crucial input for astrophysical model simulations. An interesting development occurred since the last Long Range Plan with construction of the STARLIB library, which provides experimental reaction rate uncertainties and probability densities [Sal13]. This information is particularly useful for exploring parameter sensitivities of stellar models and quantifying the nucleosynthesis outcome.

Nuclear structure and reaction data are crucial to the prediction of astrophysical simulations. Noteworthy high-profile applications include, as mentioned earlier, "kilonova" or the light that emerges from two merging neutron stars after the formation of the heaviest elements. It is thus of paramount importance that nuclear data be as complete, reliable, and up to date as possible. There are, however, significant deficiencies in the USNDP efforts in these regards. For example, the ENSDF mass chain evaluations are at present, on average, out of date by at least a decade, and ENDF does not provide reaction information on unstable nuclei. This poses a significant problem for the nuclear astrophysics community to maintain up-to-date libraries of thermonuclear reaction rates.

In the future, the field of nuclear astrophysics will see a continued transformation by the increased use of hybrid modeling that mixes theoretical and measured data, for example using Bayesian models, neural networks, evolutionary models, and other machine learning algorithms. One of the main goals will be to investigate, and reliably quantify, the impact of nuclear reaction and structure data uncertainties on astrophysical simulations. Such studies will be indispensable for motivating new measurements in nuclear physics laboratory world-wide, and ultimately pushing the boundary of nuclear astrophysics.



Figure 9.5: 2 Example of ^{99}Tc use in nuclear medicine.

The use of nuclear data is ubiquitous in modern society. In fact, nuclear data are used in so many different areas benefitting society that it is often overlooked. Household items, industry and scientific applications all use nuclear isotopes. For example, ^{85}Kr that has a 10-years half-life is found in indicator lights in household appliances, used in the assemblies of spark gaps of jet engines and commonly included in various materials for textile purposes. Fire and smoke alarms utilize the α -decay of ^{241}Am while ^{63}Ni can be found in surge protectors. In contrast, scientific geochemical studies of chondrites use ratios of long-lived radioactive actinides to characterize and date extragalactic material while rare earth nuclides inform researchers regarding the conditions of the solar system at the formation time of the moon.

The use of nuclear data has significant advantages for society. While the prospect of fusion-powered reactors remains a long-term objective, the recent observation of ICF ignition at NIF highlights the relevance and potentially societally transformative role that nuclear-data enabled applications represent. Security can be gained by non-proliferation in which it is important to detect and monitor fuel cycle activities as well as the movement of nuclear materials. The continual funding of nuclear reactions and radioisotopes supports scientific understanding of complex processes. While regulations and controls can inhibit some use of radioactive materials, the study of these properties can be used to inform policymakers, e.g. with pollution control, space-based applications, and public safety. It is thus important to properly understand and communicate the risk/reward balance. In nuclear medicine, the choice of a radionuclide that is used in a specific application depends on: the decay data, which determine its suitability for organ imaging or internal therapy and the reaction cross section data that allow optimization of its production route.

Multiple applications benefit from a robust pipeline of nuclear data. Future needs include the knowledge of reactions on unstable isotopes, quantified uncertainties associated with measurements as well as theoretical nuclear data, and the coupling of nuclear structure and decay data with reaction data. These needs can only be accomplished

through the continual funding of modern tools and infrastructure. This must be paired with a firm commitment to hiring and training nuclear data evaluators, processors, and validators.

BIBLIOGRAPHY

[Ahn19] S. Ahn *et al.*, Phys. Rev. C100, 044613 (2019).

[Ber22] L. Bernstein *et al.*, "[First Report of the Nuclear Data Charge Subcommittee of the Nuclear Science Advisory Committee](#)", NSAC Report.

[Esc18] J. Escher *et al.*, Phys. Rev. Lett. 121, 052501 (2018).

[Ili16] C. Iliadis *et al.*, Astrophys. J. 831, 107 (2016).

[Kaw20] T. Kawano *et al.*, Nucl. Data Sheets 163, 109 (2020).

[Kol22] K. Kolos *et al.*, Phys. Rev. Res. 4, 021001 (2022).

[Kon17] F. Kondev *et al.*, "[White Paper on Nuclear Data Needs and Capabilities for Basic Science](#)".

[Nel22] A. Nelson, "[Ensuring Free, Immediate, and Equitable Access to Federally Funded Research](#)", OSTP memo, 25 Aug. 2022.

[Rat19] A. Ratkiewicz *et al.*, Phys. Rev. Lett. 122, 052502 (2019).

[Rau00] T. Rauscher and F.K. Thielemann, At. Dat. Nucl. Dat. Tab. 75, 1 (2000).

[Sal13] A. Sallaska *et al.*, Astrophys. J. 207, 18 (2013).

[Spy14] A. Spyrou *et al.*, Phys. Rev. Lett. 113, 232502 (2014).

[Tri14] R. Tribble *et al.*, Rev. Prog. Phys. 77, 106901 (2014).

[Wie21] M. Wiedeking *et al.*, Phys. Rev. C 104, 014311 (2021).

[Zha15] X. Zhang *et al.*, Phys. Lett. B 751, 535 (2015).

10 SYNERGY BETWEEN RADIONUCLIDE SCIENCE AND THE NUCLEAR STRUCTURE/NUCLEAR REACTION (NSNR) COMMUNITIES

The nuclear science community requires nuclides that meet specific chemical and radioisotopic purity to measure nuclear data, explore the bounds of the periodic table, and study fundamental nuclear structure, amongst many other applications. While providing isotopes is under the purview of the Department of Energy Isotope Program (DOE-IP), there is overlap in interest and expertise between scientists funded by DOE-IP and the Department of Energy Nuclear Physics program (DOE-NP). Actively looking for opportunities to nurture this overlap will result in better science and applications for the nation.

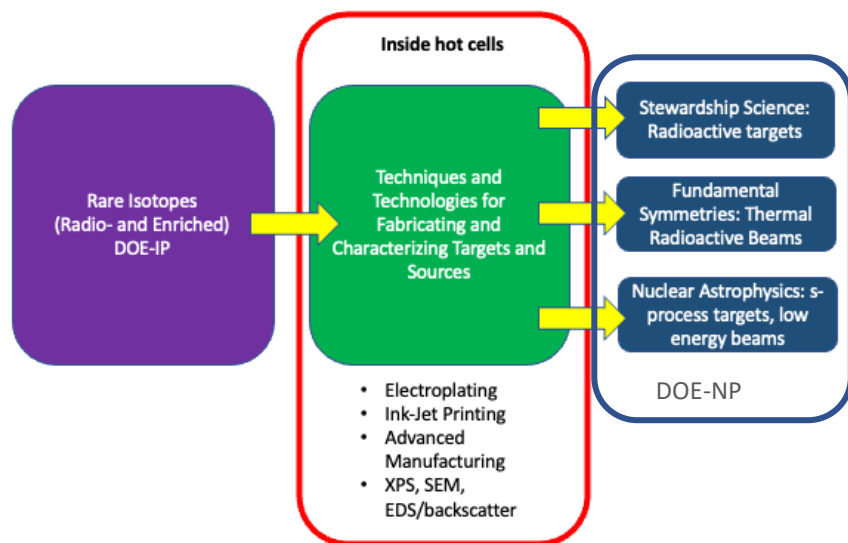


Figure 10.1: Isotopes enable science ↔ Science enables isotopes.

ISOTOPE HARVESTING AT NSCL/FRIB

One place where the benefits of synergistic overlap is obvious is at the DOE-NP funded FRIB, where isotope harvesting will provide a fertile ground for research and development. Alternative sources of radionuclides besides traditional direct production routes have been explored in recent years. With FRIB coming online, isotope harvesting has the potential to be a novel source of radionuclides to support a variety of NP experiments, as well as other national needs.

During routine operation at FRIB, the stopping of primary beams in the water-filled beam dump will create a plethora of different radioisotopes. Isotope harvesting is designed as a commensal activity that will run in the background of FRIB's nuclear physics mission. Several exploratory studies at the NSCL demonstrated the feasibility of this approach, yielding an array of different techniques that can be applied to isotope harvesting. While the operational phase of FRIB commenced in May 2022, the installation of the isotope harvesting infrastructure is currently underway. In addition to the collection of isotopes from the aqueous beam dump, solid harvesting efforts will focus on the extraction of radionuclides that accumulate in accelerator components during normal operation. This method is complementary to aqueous harvesting and will be particularly beneficial to access longer-lived and easily hydrolysable radioisotopes.

Once isotopes have been harvested, however, there is still a significant gap in the experimental process between production and utilization in a nuclear physics or chemistry experiment. Due to the collection of a broad range of fragmentation products, isotope harvesting at FRIB is inherently not selective and requires separations and to date has capitalized on decay-based purification (generator pairs). Complex radiochemical separations, and the laboratories that are equipped for these processes, are required to obtain elementally pure samples. To further purify isotopically, another approach would envision the establishment of an on-site mass separator. Even after this process, the translation of the purified product to a target must be considered. The radionuclides either would have to be shipped to another facility or, particularly for short-lived species harvested at FRIB, onsite target-production capabilities will be required.

NEW TECHNOLOGIES TO ENABLE THE ISOTOPES, ISOTOPIC BEAMS AND ISOTOPIC TARGETS FOR THE NUCLEAR PHYSICS ENTERPRISE

Neutron reaction rates on radioactive isotopes are relevant to a host of applications ranging from nucleosynthesis to national security, but very few of the important measurements have been performed due to technical challenges associated with the measurements. Modern facilities and advanced instrumentation are opening new doors to this arena, but progress will be stymied without the necessary radioisotope production, separation, and sample fabrication capabilities.

Within the U.S., LANSCE and NIF offer significant prospects for neutron reaction studies using radioactive samples. The LANSCE facility has capabilities to measure neutron capture, transmission, and (n,Z) reactions using the time of flight technique, and is investigating the potential of performing neutron reaction measurements in inverse kinematics. NIF at LLNL is developing the capability to perform fast-neutron activation measurements using fusion-produced neutrons. These studies cover a higher energy regime than complementary neutron facilities such as reactors or lower flux DD/DT sources. Radioisotope production and sample fabrication will be essential to the success of these capabilities.

Current radioisotope production capabilities that can be easily coupled to experimental nuclear physics facilities exist at LANL's Isotope Production Facility (IPF), the Brookhaven Linac Isotope Producer (BLIP), ORNL's High Flux Isotope Reactor (HFIR), the Facility for Rare Isotope Beams (FRIB), the Paul Scherrer Institut (PSI) in Switzerland, and the Institut Laue-Langevin (ILL) in France as well as the University Isotope Network (UIN). These facilities exploit a combination of high-energy protons, reactors, and heavy ion beams to enable production of a wide range of radioisotopes.

NOVEL TECHNIQUES FOR RADIOACTIVE TARGET PRODUCTION

Radioactive targets needed for the aforementioned applications in nuclear science have additional challenges that are either non-existent or less problematic with stable targets. These include but are not limited to: engineering and administrative controls associated with handling radioactive materials of varying activity levels, limited characterization opportunities, dedicated tools and spaces for production, highly valuable, limited and often short-lived target material. Radiochemical purifications are often required immediately before target fabrication to minimize decay product impurities. Furthermore, both thick and thin targets are used in the community for different applications, and each have their own sets of challenges needing advancement. For instance, thick targets often suffer from poor adhesion and inhomogeneities while thin targets are typically very fragile. Fundamental studies in adhesion between backings and depositions as well as targets to withstand high beam currents would support both regimes. Given the comparatively limited investigation into radioactive target production techniques, there is a need

for research in both traditional methods (e.g. electrodeposition, vapor deposition, etc.) as well as new approaches (e.g. additive manufacturing, ink jet printing, solution combustion synthesis).

An example of radioactive target production that has been an active area of research to support nuclear science and stockpile stewardship studies is the fabrication of thin, robust, and isotopically pure actinide targets.

NOVEL TECHNIQUES FOR ACTINIDE TARGET PRODUCTION

Thin, robust, and isotopically pure targets of actinides have remained a challenge for decades. Conventional techniques for actinide target preparation consume expensive and hazardous radioactive materials and result in fragile, breakable targets.

Notre Dame's Nuclear Science Laboratory has developed innovative new approaches for the preparation of thin actinide targets that are robust with controlled thicknesses. The innovation lies in the implementation of state-of-the-art material science approaches that use solution combustion synthesis (SCS) reactions between actinide metal nitrates with organic compounds. Rapid exothermic processes coupled with various deposition methods are used to deposit thin targets on a variety of different backings. Low concentrations of the combustible solution layers are deposited on the desired backings by spin coating, spraying, or inkjet printing. These deposition procedures provide precise control over the target thicknesses and efficient use of actinide materials. The targets are made following the determination of the best reaction dynamics conditions. Accelerators at the Nuclear Science Laboratory at Notre Dame are then used to irradiate the prepared targets to test the sturdiness or robustness of the targets. Tests have shown that the layers do not disintegrate or lose adherence to the backing even irradiating with Argon beams of 1-2 MeV and fluences of 10^{17} ions/cm². A large array of imaging and spectroscopic tools is used to precisely characterize the resulting targets including high-resolution electron microscopy, diffraction methods, and alpha-particle spectroscopy before and after irradiation to search for signs of degradation.

The development and testing of targets is being carried out in collaboration with the national science laboratories including LANL, LLNL, and ORNL and helping private industry. The experience and knowledge resulting from these novel approaches in target preparation are also used to help the growing medical isotope industry in the production of radionuclides for medical research, diagnosis, and treatment.

A key capacity gap remains: while the community has the ability to perform chemical separations, the ability to isotopically purify radioactive samples has been lost. Isotopic impurities induce additional background and unnecessary risk due to high activity, and degradation of the quality of measurements using radioactive samples. The long-term success of nascent radionuclide measurement capabilities will hinge on the community's ability to provide isotopically enriched samples.

The routine production of high specific activity radioactive targets is a challenge that needs to be addressed in the workforce and technological capabilities in the immediate future and investment in all aspects of this effort is encouraged.

UNIVERSITY ISOTOPE NETWORK

The Department of Energy (DOE) Isotope Program has created a University Isotope Network to leverage a nationally distributed, complementary, and growing collection of university-based accelerators (whose primary mission and

support is outside of the DOE-IP) to meet special national needs for isotopes. The UIN coordinates effort at these commercial production cyclotrons and higher (up to K500) energy accelerators with available proton, deuteron, alpha, and heavy ion beams, often coupling irradiations with radiochemical isolation and/or subsequent custom fabrication capabilities, to deliver unique radioactive materials to researchers and industry partners. These activities are conducted on a cost-recovery basis and support fundamental scientific inquiry and technology/applications development. The network also facilitates interaction between its members, who can take advantage of their connection to DOE expertise, resources, and facilities in the national laboratory system, and increases the visibility of and access to these resources.

IMPROVEMENT OF NUCLEAR REACTION MODELS

One of the challenges in this field is determining the best nuclear reaction to produce isotopes that have been identified as potentially useful for cancer therapy. Presently, significant effort is required to identify the best route to produce the desired isotopes with both high yield and radio-purity. Production via compound nucleus (fusion evaporation) reactions using light ion beams from protons to lithium is often the mechanism of choice. However, the production cross sections and their excitation functions, as well as the achievable radiological purity is not consistently predictable from existing reaction codes such as PACE, TALYS, and Empire and often significantly vary within factors of 2-10. Hence, time consuming data collection is required to determine the best production approach. Addressing this shortcoming of the nuclear models to improve the accuracy of their predictions is a field of research to be addressed through collaboration of the medical isotope and the nuclear structure / nuclear reactions (NSNR) communities. The NSNR community has the tools to address this fundamental need of the medical isotope community. The recent upgrade of the electronics and related data acquisition of Gammasphere, for example, combined with the available ion beams at ATLAS in the compound-nucleus/fusion-evaporation energy regime applied to this need can contribute significantly to the required data collection for the development of medical isotopes. Dozens of potentially interesting medical isotopes, especially positron and Auger-electron emitters can be made with high yields using this reaction mechanism. Generally, the same isotope can be produced via several different ion beam and target combinations. Many well-known medical isotopes for both diagnostic and therapeutic applications are produced routinely with protons or deuterons at low energy medical cyclotron facilities with beams of ~10-25 MeV in energy; however, many additional isotopes can be produced with heavier light ions such as ^3He , ^4He and ^6Li . Simulations of the yields with proton- and deuteron-induced reactions are typically good because of better-known nuclear optical potentials needed as input to the reaction models. However, cross sections for the helium and lithium induced reactions with cross sections in the barns range are typically not well reproduced by the models due to the unknown optical potentials. Therefore, to choose the optimal beam, (isotopically enriched) target, and energy range for production of specific isotopes requires extensive experimentation. There are several medical isotope production sites in the U.S., some of which have helium and lithium ion beams, and some of these also have NSNR research groups. Since there are several sites in the U.S. that have an array of appropriate beams, large gamma arrays (Gammasphere, Hyperion, GRETINA/GRETA) and NSNR research groups, there is a synergy between the interests and capabilities of these groups and facilities.

Research on the production of therapeutic medical isotopes is a high priority mission of DOE-IP and presents a prime opportunity for collaboration between IP and NP. A possible scenario to streamline the optimization of production routes builds on the synergy between the interests and capabilities of the medical isotope and NSNR communities. For example, running in Gammasphere at ATLAS (or Hyperion at Texas A&M) for a few days of the various target/beam combinations, the required excitation functions can be mapped out. Furthermore, such data can be used together with AI/ML methods to improve nuclear models. As the nuclear models are improved the need for

detailed measurements of excitation will be reduced. Such data and improved nuclear models will benefit the medical isotope community which will immediately benefit from the on-going research of the NSNR community which is aimed at streamlining data analysis from complex data sets from Gammasphere, Hyperion and other large-scale gamma arrays such as GRETINA/GRETA by applying AI methods. Overall, such developments require the capabilities of several accelerator facilities including ATLAS, Texas A&M and the LBNL 88" Cyclotron which have external ECR ion sources to deliver higher intensity light ion beams.

WORKFORCE DEVELOPMENT

As we have demonstrated, radionuclide science is vital for the elucidation of some questions in NSNR. Radionuclide science requires collaboration across isotope production, radiochemical separations, target fabrication, nuclear physics, theory, evaluation, and computational communities where limitations in an individual community will affect the whole. Research radioisotope production, sample fabrication, and radioisotope measurements represent developing fields, with most of the relevant knowledge and expertise concentrated in a few key individuals. To ensure the long-term success of these fields, we must create a sustainable pipeline to nurture the developing talent pool, providing adequate training facilities, and allow effective mentorship of the next generation.

Workforce development is one obvious example of an area where the Office of Nuclear Physics and Isotope Program goals are synergistic. Because isotope production is so interdisciplinary, skills in many areas of study are required in order to fulfill national needs for isotope production. Many of these skills in chemistry, physics, material science, biological sciences, computation, and nuclear engineering are also developed during training for degrees in nuclear physics. There is also overlap of skill set in the sorts of experiments that are run, such as measurements of cross sections of isotopes that are not already routinely produced. These areas of overlap are mutually beneficial and require nurturing. The Isotope Program recently funded a large group of universities under HIPPO, the Horizon-broadening Isotope Production Pipeline Opportunities program, which has PIs and students participating in several of the areas outlined above. The fact that this program is based at Texas A&M University and includes other UIN facilities has already attracted students who were previously unaware of opportunities in isotope production, and has resulted in one student performing a post-baccalaureate semester at Argonne National Lab, where he participated in horizon-broadening research.

Investment in pipeline development is playing a long game, and it works. Several of the co-investigators of HIPPO are the product of or now involved in the DOE/American Chemical Society Nuclear & Radiochemistry Summer Schools at Brookhaven National Laboratory and San Jose State University. Broad investments in workforce development are vital to enable the next generation of ground-breaking experiments and further technology development.

OPPORTUNITY FOR COOPERATION WITH EUROPEAN COLLEAGUES

The European Rare Stable Isotope Supply (EURASIS) initiative has been started by the European Nuclear Physics community in the framework of the next NuPECC Long Range Plan (LRP), which is being prepared almost synchronously with the NSAC LRP in the USA, to respond to the present challenges of rare stable isotope supply for fundamental nuclear research in Europe.

The supply shortage of enriched stable samples (ESI), severely aggravated by the Russian aggression against Ukraine and its consequences, calls for a solution with the aim to warrant a secure provision of European research

institutions. Without these basic materials, essential fundamental research activities will come to a halt, once the still available limited reserves are consumed.

The situation is affecting not only the nuclear physics community but also research in nuclear medicine applications, Mössbauer spectroscopy and neutrino-less double- β decay. A concerted action plan is urgently needed, in synergy with all disciplines and communities concerned. The international character of fundamental research and the respective scientific collaborations demands an international and discipline-overarching effort to solve this global problem.

For some production schemes and isotopes, like ^{48}Ca , ^{176}Yb and other isotopes enriched by the electromagnetic isotope separation (EMIS) technique, Russian institutions have historically been the main, if not only, sources of supply. One way out from the dependence on unsecured extra-European (Russian) supply could be the set-up of a European infrastructure, providing technology and capacities meeting the European needs of ESI. Measures to mitigate this dilemma could include the implementation of an EMIS facility in Europe, ideally embedded in an international network.

This initiative emerging from the European nuclear physics community has the aim to assure European Rare Stable Isotope Supply (EURASIS) for research, promoting a concerted effort of all scientific and research communities affected.

In our view this is a burning issue and an opportunity for collaboration between the US and Europe. Private industry may also provide some avenues for collaborative research as well as by providing isotopes for use in research. Finding a solution should be made a prominent topic of the long range planning process both in the US and Europe.

HORIZON-BROADENING ISOTOPE PRODUCTION PIPELINE OPPORTUNITIES



Michael Jones (The University of Alabama at Birmingham student) tries out the IPF hot cell, while a technician explains his process to another HIPPO student.

The HIPPO program kicked off on summer of 2022 with a strong emphasis on workforce development for the Isotope Program. Twenty-five students (10 graduate, 15 undergraduate) participated in the inaugural class, and participated in research across DOE labs and universities involved in different aspects of isotope production. The focus was on broadening the horizons of the students, so graduate students participated in horizon-broadening research away from their home institution, and the students visited Los Alamos National Lab for a week in July to learn more about the Isotope Production Facility there.

11 INTERSECTION WITH FUNDAMENTAL SYMMETRIES, NEUTRONS, AND NEUTRINOS

The connection between nuclear structure/reactions and tests of the fundamental symmetries of nature has historically played a major role in nuclear science, from characterizing the necessary dynamics and properties of the nuclear force to discovering the violation of parity symmetry in nuclear decay. More recently, the interface between these two communities has focused on trying to understand the unusual properties of neutrinos, searching for new violations of basic symmetries in subatomic forces, and performing precision tests of the present Standard Model of the strong, weak, and electromagnetic forces. Since the last LRP in 2015, there have been major advances in several connected research areas –the most significant of which, perhaps, are those made in nuclear theory.

Among the main thrusts from the FSNN community is elucidating the nature of the neutrino - an area of research that is deeply rooted in NP and has significant connections to the structure, astrophysics, and reactions community. The primary focus regions of this research are the search for neutrinoless double beta ($0\nu\beta\beta$) decay, absolute neutrino mass measurement via beta decay, and understanding neutrino-nucleus interactions and scattering from nuclei as input for precision short- and long-baseline experiments. These experiments probe a wide range of energies and momenta -- from the low energy regime of beta decay to the quasielastic regime of neutrino scattering processes relevant to neutrino oscillation experiments -- which makes this research heavily interdisciplinary with strong connections to both astrophysics and HEP, thus providing a nice bridge between the structure/astrophysics as well as the particle physics communities.

Precision measurements of nuclear structure and decay properties continue to play a significant role in the FSNN community. The flagship program in this area has traditionally been testing the unitarity condition of the CKM matrix using the top-row sum by extracting V_{ud} through structure measurements of superallowed Fermi beta decay and the associated theoretical corrections that are required. This remains one of the highest precision tests of the SM that our community has achieved and will remain a focus for the next decade. Similar systems are also currently used to search for exotic scalar and tensor currents in the weak interaction through precision structure and decay measurements. The next-generation experimental work in this area will exploit superconducting quantum sensing technology – work that has already begun.

Recent advances in quantum manipulation and sensing of radioactive atoms and molecules have accelerated BSM searches for permanent electric dipole moments (EDMs). Significant enhancements in these searches are enabled by using heavy, octupole deformed nuclei, and thus understanding the nuclear structure of these systems is critical. Much of the current work in this area is synergistic with the structure community and is focused on spectroscopic measurements using lasers.

Five research areas were selected by the conveners as topics for the “intersections session” at the structure Town Hall meeting and are briefly summarized in the subsections below. This format was chosen since the FSNN community at-large conducted their own Town Hall meeting in December 2022 with a separate whitepaper on all activities and recommendations for that field, including community consultation and input. This whitepaper, and the 20 others that were submitted to the FSNN Town Hall meeting, contain more detailed information than what is contained in this section, and can be found at <https://indico.phy.ornl.gov/event/209/page/99-white-papers>.

NUCLEAR STRUCTURE RELATED TO $0\nu\beta\beta$ DECAY MATRIX ELEMENTS

Accurate transition matrix elements, commonly referred to as nuclear matrix elements (NMEs), are a crucial ingredient for the design of neutrinoless double beta decay experiments, as well as the extraction of the absolute

neutrino mass scale from a hypothetical observation. Most of the candidate nuclei for detectors have a rich intrinsic structure that poses a serious challenge to microscopic nuclear structure theories. At the time of the 2015 LRP, a wide variety of methods had been applied to the calculation of NMEs, yielding results that varied by factors of 2 to 3 [Eng17]. Since all calculations were based on (mostly) empirical interactions and assumptions that were fine tuned to each particular framework, systematic improvements, uncertainty analysis, or even a meaningful cross validation were not possible. To tackle this issue, the U.S. ab initio nuclear structure community (and select international collaborators) launched a joint effort that was supported by the Department of Energy through a Topical Collaboration. In recent years, this has resulted in a first wave of ab initio NMEs that are consistent within the used methods capabilities for capturing correlations when calculations are using the same interaction and operators as input (see [Cir22] for a recent overview).

The main goal for the next phase of this effort is to improve upon all aspects of the first-generation results by enhancing the methods, consistency, and producing systematic theoretical error bars. Since ab initio nuclear structure calculations are computationally expensive, surrogate models or emulators will play a crucial role in sensitivity analyses and uncertainty quantification. There have been impressive developments in this area in the nuclear theory community in recent years (see, e.g., [Mel22], [Bon22], and references therein), but more work is necessary to meet the needs of the neutrino-less double beta decay program and other fundamental symmetry efforts.

As systematic truncations and approximations of modern many-body methods are relaxed, their computational cost is also going to increase – and it is important to realize that this growth cannot be avoided using emulators alone, because at the very least, the full calculations are necessary to train the emulators. Thus, there is a need for continuous optimization of the computer codes, to ensure that applications are as efficient as possible, and make best use of the available computing resources. Given the complexity of modern heterogenous high-performance computing platforms, this will require support from experts with a (research) software engineering background, e.g., through national computing facilities or HPC system vendors. In this context, another important aspect is to ensure long-term support for maintaining codes – present options tend to be more focused on porting software to new computing resources.

The complexity of the problem will require dedicated personnel working on nuclear many-body theory, EFT, math, and statistics, as well as computation, and progress will rely on sustained access to high-performance computing resources, including those at leadership facilities. Fortunately, many of the aforementioned needs overlap with the needs of the ab initio nuclear structure and reactions programs, and potential synergies can be exploited.

BSM PHYSICS SEARCHES USING NUCLEAR BETA DECAY

There exists a wide variety of nuclear systems and probes that provide enhanced sensitivity to phenomena that can arise due to beyond the Standard Model (BSM) contributions to the electroweak interaction [Gon19]. At the level of precision currently being achieved for this type of fundamental symmetries research, numerous higher-order corrections need to be accounted for through nuclear (structure) theory [Har10]. In addition to progress on improving the determination of electroweak radiative corrections [Sen18, Cza19, Hay21, Shi21a], one of the most dramatic developments has been the emergence of new many-body methods with controllable uncertainties that can be applied in a wide range of relevant nuclei [Her20]. This progress is not only an intersection between nuclear structure and fundamental symmetry, but it has also set the stage for productive interactions between theory and experiment to reassess and sharpen theoretical uncertainties and to interpret the high-quality data being collected with advanced experimental systems.

One of the central goals for the coming years is to place the on-going work with allowed decays on a more rigorous theoretical footing and push the precision frontier for the experimental campaigns targeting a set of key nuclei. The ab-initio theory community plays a particularly important role in this endeavor by providing improved theoretical estimates for the nuclear structure effects in the radiative δ_{NS} and isospin breaking δ_C corrections necessary for extracting the V_{ud} element and improving the results for the "top-row" unitarity test. Furthermore, searches for exotic couplings will also rely more heavily on improving the nuclear structure corrections that are currently on the order 1% as measurements campaigns now aim for 0.1% precision or beyond. It has already been shown, for the ${}^8\text{Li}$ decay, that theoretical uncertainties in the calculation of recoil-order terms can be reduced significantly if a proper treatment of collective features in nuclei is included [Sar22]. Nuclear structure and fundamental symmetries intersect not only on the theory side but also experimentally where current and future technical developments is or might benefit both communities. These includes advances in high-precision mass spectrometry, the growing use of superconducting tunnel junctions, and cyclotron resonance spectroscopy (CRES).

STRUCTURE AND SYMMETRY STUDIES WITH ATOMS AND MOLECULES

Precision studies of atoms and molecules allow the exploration of physical phenomena encompassing a wide range of energy scales [Saf18]. In atoms, laser spectroscopy measurements have proven to be unique tools to access the electromagnetic properties of nuclei (nuclear radii, spins, magnetic dipole, octupole, and electric quadrupole moments) at the extremes of existence [Yan22]. Such experiments have been critical to guide developments of modern nuclear theory and its connection to the fundamental theory of quantum chromodynamics (QCD) to further our understanding of nuclear structure [Kos21,Ver22].

Adding or removing neutrons to/from an atomic nucleus induces changes in its nuclear charge distribution, causing minute perturbations in the energies of its bound atomic electrons, known as isotope shifts. High-precision measurements of these isotope shifts have been established as a powerful means to study diverse physical phenomena, ranging from low-energy nuclear to high-energy particle physics [Ant19, Gar16, Sta18, Ber18, Udr21]. To first order, isotope shift measurements are sensitive to changes in the distribution of protons inside the nucleus [Gar16, Gro20]. However, if enough nuclear properties can be sufficiently well constrained, precision measurements of isotope shifts can probe the existence of new particles [Sta18, Hur22].

Complementary to atoms, molecular systems offer new opportunities to investigate unknown aspects of the fundamental forces of nature and the violations of fundamental symmetries: time-reversal (T), parity-invariance (P) and charge-conjugation (C) [Saf18]. Currently, the most stringent limits on the T-violating electron electric dipole moment (eEDM) have been set by measurements in molecular systems, constraining the existence of new physics beyond the Standard Model at the TeV scale [Andr18].

Molecules can be very sensitive to nuclear properties, violations of fundamental symmetries and new particles and/or forces of nature as illustrated in Figure 11.1. In molecules, symmetry-violating effects scale strongly with the atomic and mass number, nuclear spin, and nuclear deformation. Hence, radioactive molecules containing heavy, octupole-deformed nuclei such as radium, offer an extremely high sensitivity to P- and T-violating nuclear properties [Gaf13, Gar20], more than three orders of magnitude higher with respect to naturally occurring molecules. Despite the marked interest, precision experiments in these systems are challenging. Their production and study demand the development of highly sensitive experimental techniques [Gar20].

Future development of atomic and molecular techniques at radioactive beam facilities will open a new era of science with a far-reaching impact in nuclear and high-energy physics, astrophysics, chemistry and quantum sciences. The Facility for Rare Isotope Beams (FRIB) in the US, for example, will provide unprecedented access to

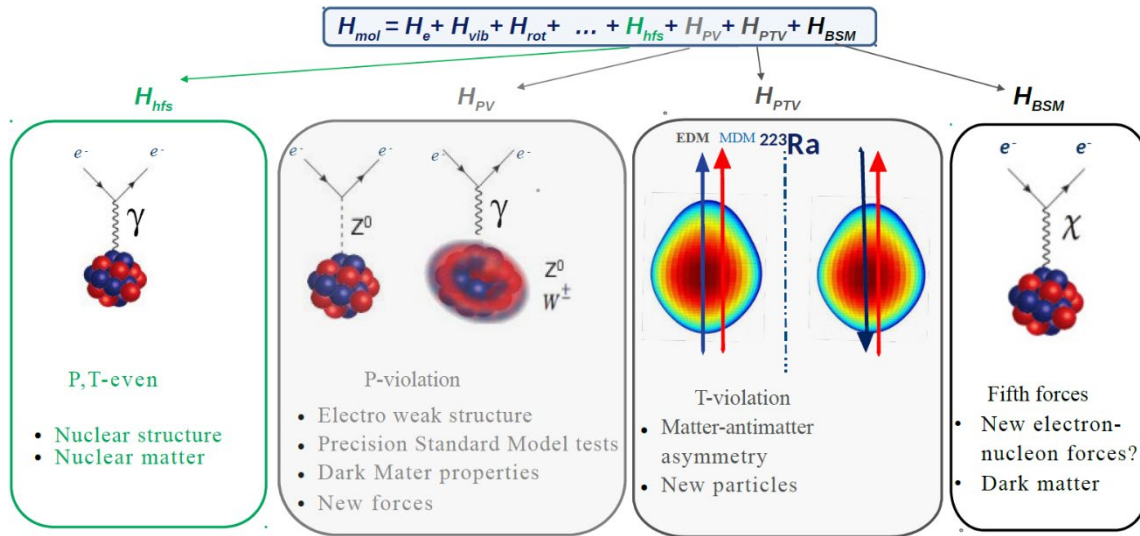


Figure 11.1: Effective molecular Hamiltonian, including beyond the SM effects. Molecular energy levels can be highly sensitive to nuclear properties, violations of fundamental symmetries in addition to possible new forces and particles of nature. Compared to atoms, molecules can offer a gain of more than five orders of magnitude in sensitivity to these effects.

octupole-deformed isotopes in the actinide region, opening a diverse range of opportunities for studies of violations fundamental symmetries. The outlook for this emerging field of research is very exciting, and opportunities to further advance this avenue of research should not be missed.

NEUTRINO-NUCLEUS INTERACTIONS

An accurate understanding of neutrino scattering from nuclei is required to extract precise information on neutrino properties and to better characterize astrophysical environments. Important experiments include accelerator and reactor measurements of neutrino oscillations, astrophysical neutrino detection from supernovae and other sources, and measurements of coherent neutrino scattering. These neutrino experiments will provide insights on the nature of neutrino masses, the neutrino mass hierarchy, the presence of CP violation, and perhaps exotic new physics in the neutrino sector.

Maximizing the discovery potential of neutrino experiments will require a theoretical understanding of neutrino-nucleus interactions and cross sections over a wide range of energy and momentum transfer where different reaction mechanisms are at play. This is a rather challenging problem whose solution requires a combination of expertise, including lattice QCD, nuclear many-body theory and computational methods for nuclear effective theories, phenomenology, and neutrino event generators to make reliable theory predictions relevant to the experimental programs.

At low energies (a few to a few tens of MeV), the dominant modes are coherent elastic neutrino scattering (CEvNS) where one observes elastic scattering of neutrinos from the whole nucleus, and inelastic processes to understand neutrinos from core-collapse supernovae and to interpret supernova burst neutrino data in large terrestrial detectors. Neutrinos from stopped-pion sources are optimal for validating theory by measuring the relevant cross sections in this energy range.

Neutrino-nucleus cross sections in the one- to few-GeV regime with quantified theoretical errors are essential to the accelerator neutrino short- and long-baseline experiments. There has been substantial progress in first principles

calculations of inclusive nuclear electroweak response. The challenge is to develop a comprehensive theory of nuclear dynamics in the wide range of energy and momentum probed by the experimental programs, including exclusive processes, and extend microscopic approaches to medium mass nuclei of experimental interest.

Neutrino scattering also plays a valuable role in fundamental symmetry tests in beta decay. Radiative corrections including quasi-elastic kinematics are important to reduce standard model backgrounds and extract precise results in searches for beyond-the-standard model physics. The highly interdisciplinary nature of the problem requires expertise in diverse fields, including lattice QCD, many-body computational methods, EFTs and phenomenology along with sustained access to substantial computational resources. Initiatives aimed facilitating and supporting interdisciplinary collaborations will be highly beneficial for progress in the FSNN field of research [FSNNTheory].

NEW EXPERIMENTAL TECHNOLOGY INTERSECTIONS

To achieve the scientific goals set out by the FS community, new experimental technologies are required – some of which are already in use. Thus, there is significant potential for adapting this technology in the NS/NA community as well and is seen as an area of significant intersection between the two. In fact, many of the experimental techniques used in FSNN research characterize (eg. V_{ud}) or exploit (e.g. nuclear EDMs) interesting nuclear structure properties to high precision. Over the past LRP, manipulation using ion traps and optical techniques have led the way in this area through precision measurements of stable and radioactive ions at both national user facilities and University laboratories. Advances in FSNN research through this intersection include: collinear laser spectroscopy at NSCL/FRIB [Kon21], precision $A=8$ decay studies in the beta decay Paul trap (BPT) at ANL [Bur22], basic tests of fundamental symmetries using neutral atom [Fen18] and ion traps [Oma20, Shi21b].

Over the next decade, quantum manipulation and sensing are poised to revolutionize measurements in both the FSNN and NS/NA communities using radioactive molecules and superconducting sensors. Further, with the development of the new cyclotron radiation electron spectroscopy (CRES) technique to measure the neutrino mass in ^3H beta decay (Project-8), new experimental searches for exotic weak currents will be possible with the ^6He -CRES experiment. This collaboration is expanding the CRES technique to span MeV-scale beta decays (thus making it applicable to the majority of structure measurements as well) and promises to attain sensitivities to exotic currents that will be unmatched, even by the LHC [Byr23].

BIBLIOGRAPHY

- [Andr18] V. Andreev *et al.*, Nature 562, 355 (2018).
- [Ant19] D. Antypas *et al.*, Nature Physics 15, 120 (2019).
- [Ber18] J. Berengut *et al.*, Phys. Rev. Lett. 120, 91801 (2018).
- [Bon22] E. Bonilla, P. Giuliani, K. Godbey and D. Lee, Phys. Rev. C 106, 054322 (2022).
- [Bur22] M.T. Burkey *et al.*, Phys. Rev. Lett. 128, 202502 (2022).
- [Byr23] W. Byron *et al.*, (He6-CRES collaboration), submitted to Phys. Rev. Lett. [<https://doi.org/10.48550/arXiv.2209.02870>].
- [Cir22] V. Cirigliano *et al.*, J. Phys. G: Nucl. Part. Phys. 49, 120502 (2022).
- [Chu19] T. E. Chupp *et al.*, Rev. Mod. Phys. 91, 015001 (2019).
- [Cza19] A. Czarnecki, W. J. Marciano, and A. Sirlin, Phys. Rev. D 100, 73008 (2019).

- [Eng17] J. Engel and J. Menendez, Rep. Prog. Phys. 80, 046301 (2017).
- [Fen18] B. Fenker *et al.*, Phys. Rev. Lett. 120, 062502 (2018).
- [FSNNTheory] B. Acharya *et al.*, [FSNN Theory Workforce LRP 2022](#); White paper submitted to the NSNN Town Hall.
- [Gar16] R.F. Garcia Ruiz *et al.*, Nature Physics 12, 594 (2016).
- [Gar20] R.F. Garcia Ruiz *et al.*, Nature 581, 396 (2020).
- [Gon19] M. Gonzalez-Alonso *et al.*, Prog. in Part. and Nucl. Phys. 104, 165 (2019).
- [Gro20] R. Groote *et al.*, Nature Physics 16, 620 (2020).
- [Hay21] L. Hayen, Phys. Rev. D 103, 113001 (2021).
- [Har10] J. C. Hardy, and I. S. Towner, Rep. on Prog. in Phy. 73, 046301 (2010).
- [Her20] H. Hergert, Front. in Phys. 8, 10.3389/fphy.2020.00379 (2020).
- [Hur22] J. Hur *et al.*, Phys. Rev. Lett., 128, 163201 (2022).
- [Kon21] K. König *et al.*, Phys. Rev. A 103, 032806 (2021).
- [Kos21] Koszorus *et al.*, Nature Physics 17, 439 (2021).
- [Mel22] J. Melendez *et al.*, J. Phys. G: Nucl. Part. Phys. 49, 102001 (2022).
- [Oma20] P.D. O'Malley *et al.*, Nucl. Instr. Meth. B 463, 488 (2020).
- [Saf18] M. Safronova *et al.*, Rev. Mod. Phys. 90, 025008 (2018).
- [Sar22] G. H. Sargsyan *et al.*, Phys. Rev. Lett. 128, 202503 (2022).
- [Sen18] C.-Y. Seng *et al.*, Phys. Rev. Lett. 121, 241804 (2018).
- [Shi21a] K. Shiells, P. G. Blunden, and W. Melnitchouk, Phys. Rev. D 104, 33003 (2021).
- [Shi21b] P.D. Shidling *et al.*, Int. J. Mass Spectr. 468, 116636 (2021).
- [Sta18] Y. V Stadnik, Phys. Rev. Lett. 120, 223202 (2018).
- [Udr21] S. Udrescu *et al.*, Phys. Rev. Lett. 127, 033001 (2021).
- [Ver22] A. Vernon *et al.*, Nature 607, 260 (2022).
- [Yan22] X. Yang *et al.*, Prog. Part. Nucl. Phys 104005 (2022).

