OLD DOMINION UNIVERSITY
COLLEGE OF SCIENCES

May 15, 2024

Dr. Harriet Kung
Acting Director, Office of Science
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. Kung:

In the letter from your office dated December 1, 2023, Dr. Asmeret Berhe charged NSAC to establish a subcommittee to evaluate new facilities and projects over $100 million in terms of (a) potential to contribute to world leading science in the next decade, and (b) readiness for construction. We received a list of projects to consider from the Office of Nuclear Physics.

Attached please find the the report from the NSAC subcommittee, which was chaired by Professor Christine Aidala, from the University of Michigan. The subcommittee membership was composed of experts in the areas covered by the NP project list, while avoiding any perception of conflict of interest. We did not add any projects to the list, mainly because of the ten-year horizon.

In responding to this facilities charge, NSAC has been guided by the scientific priorities laid out in the 2023 Long Range Plan (LRP) and the discussions held as part of the LRP process. As you know, neutrinoless double beta decay and the EIC are the highest priority for new experiments/facilities for our community and were listed as Recommendations #2 and #3 in the Long Range plan. These two projects are **absolutely central** to our field.

LRP recommendation #4 encompasses additional projects and new strategic opportunities to advance discovery science. The remaining projects we were asked to evaluate as part of this charge are examples of strategic opportunities to advance discovery science. These additional projects are **critically important** to the field and to maintaining U.S. leadership in nuclear science. Several of the projects take advantage of previous investments at national user facilities. Most of these projects have already been vetted and reviewed, which is why they were called out in the Long Range Plan. The fact that these projects are on the list from NP is a testament to their very high level of importance to our field.

The subcommittee critically examined the readiness for construction for each project, based on input from the project leaders and from the Office of Nuclear Physics.

The subcommittee report was presented to NSAC during its April 26, 2024 meeting. Following discussion, the report was approved unanimously. I would be happy to answer any questions you may have about the report.

Sincerely yours,

Gail E. Dodge
Chair, NSAC

cc: Linda Horton, DOE
Denise Caldwell, NSF
Allena Opper, NSF

Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Facilities Subcommittee

May 1, 2024

DOI: https://doi.org/10.2172/2476337

Summary

On December 1, 2023, the Department of Energy Office of Science issued a charge to the federal advisory committees to "consider what new or upgraded facilities in your disciplines will be necessary to position the Office of Science at the forefront of scientific discovery." We were directed to consider projects over $100 million that are envisioned for the next decade (see Appendix A for the full charge) and form a subcommittee to evaluate, for each project, (i) the potential to contribute to world-leading science in the next decade and (ii) the readiness for construction.

As directed in the charge letter, the DOE Office of Nuclear Physics (DOE NP) provided a list of projects to the Nuclear Science Advisory Committee (NSAC), along with their current status:

- Electron-Ion Collider (EIC)
- High-Rigidity Spectrometer (HRS)
- Ton-Scale Neutrinoless Double-Beta Decay (TS-NLDBD)
- Project 8
- Facility for Rare Isotope Beams Energy Upgrade (FRIB400)
- Solenoidal Large Intensity Device (SoLID)
- Electron-Ion Collider (EIC) Detector II

The full list and descriptions provided by DOE NP is included as Appendix B.

The nuclear science community has a proud tradition of producing thoughtful and impactful Long Range Plans (LRP), dating back to 1979. We work hard to reach consensus and articulate our priorities for the science in the coming decade. Much of the vision captured in the 2015 Long Range Plan has been implemented, and we are witnessing the fruits of those investments. Our community recently completed a new long range plan, titled *A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science*, available at NuclearScienceFuture.org and on the NSAC Reports page. The 2023 LRP process involved town meetings organized by the American Physical Society Division of Nuclear Physics and input from the community in the form of two dozen white papers. A broad and diverse committee of 62 nuclear scientists, including two international observers, wrote the LRP, which includes four high-level recommendations (Appendix C) in the Executive Summary.

In responding to this facilities charge, NSAC has been guided by the priorities laid out in the 2023 LRP and the discussions held as part of the LRP process. A small Subcommittee composed entirely of members of the LRP Writing Committee was chosen, with the goal of including expertise on the projects under consideration, while avoiding institutional conflicts of interest. The members of the Subcommittee are listed in Appendix D. The charge to the Subcommittee is included in Appendix E. The Subcommittee requested and received feedback from the leaders of each project relevant to both the importance of the science and the readiness for construction. The Subcommittee met four times via Zoom: January 31, February 28, March 5, and March 19, 2024.

The importance of the science for each project as assessed by the Subcommittee was tied closely to the 2023 LRP. Recommendation #1 of the 2023 LRP addresses the need for investment in research and effective operations of the national user facilities. Recommendations #2 and #3 "reaffirm the exceptionally high priority of the following two investments in new capabilities for nuclear physics. The Electron-Ion Collider (EIC), to be built in the United States, will elucidate the origin of visible matter in the universe and significantly advance accelerator technology as the first major new advanced collider to be constructed since the LHC. Neutrinoless double beta decay experiments have the potential to dramatically change our understanding of the physical laws governing the universe." These two projects have been evaluated by the nuclear science community as **absolutely central** to maintaining U.S. leadership in the field and answering the key scientific questions of our time. Recommendation #4 encompasses additional projects and new strategic opportunities to advance discovery science. The remaining projects we were asked to evaluate as part of this charge are examples of strategic opportunities to advance discovery science. These additional projects are **critically important** to the field and to maintaining U.S. leadership in nuclear science. Several of the projects take advantage of previous investments at national user facilities.

In considering the readiness for construction the Subcommittee was guided by the current status of the project and remaining challenges, including the DOE critical decision level, if any. We noted that a large gap exists between rating (a) ready to initiate construction and (b) significant scientific/engineering challenges to resolve before initiating construction. Projects that do not have significant scientific or engineering challenges were given a rating of (a), but in each case we explain the status and any special circumstances affecting readiness. The table below summarizes our ratings, and the pages ahead discuss these ratings in more detail.

Scientific importance categories: (a) absolutely central; (b) important; (c) lower priority; (d) don't know enough yet.

Readiness for construction categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; (c) mission and technical requirements not yet fully defined.

Project	**Scientific Importance**	**Readiness for Construction**
EIC	**a**	**a**
HRS	**b**	**a**
TS-NLDBD	**a**	**a**
Project 8	**b**	**c**
FRIB400	**b**	**a**
SoLID	**b**	**a**
EIC Detector II	**b**	**c**

Cross-cutting Opportunities

The Subcommittee was also asked to address cross-cutting interests and connections, including the scientific interest our community has in specific facilities under consideration by other DOE Office of Science programs. The 2023 Long Range Plan addressed several cross-cutting topics, including in the broad areas of computing and sensing, accelerator and detector research and development, and the importance of nuclear data in advancing basic and applied science.

EIC Interest in Scientific Computing Facilities

The Electron-Ion Collider (EIC) will investigate the structure of nucleons and nuclei at an unprecedented precision. The first scientific collaboration for the EIC, ePIC, was formed in 2023 to facilitate the realization of the DOE EIC Project detector. In the context of the SC Facilities Charge, two aspects of the ePIC computing model should be emphasized: streaming readout and autonomy. ePIC will utilize streaming readout for its data acquisition system, capturing every collision signal, including background. Physics events will undergo near-real-time reconstruction from the streaming data, including automated alignment, calibration, and validation. This presents a challenging real-time workload that aligns well with the time-sensitive pattern of the Integrated Research Infrastructure. This workload will utilize advanced features of modern networking provided by ESnet. The real-time processing could also benefit from a "Spoke" associated with the HPDF. The control of the ePIC experiment and the processing of its data will have an unprecedented level of autonomy. Partnership with the ASCR ecosystem is essential to develop such functionality.

Other Computing Needs

Advanced high-performance computing (HPC) is essential to accomplishing the priority research directions in nuclear science. For large-scale simulations that range from subnucleonic to astrophysical, a portfolio of analytic methods, numerical methods, and domain- and priority-specific codes continue to evolve to optimize scientific impact from current and near-term computing hardware of diverse, heterogeneous architectures. With increasing numbers of nuclear physics applications becoming exascale ready, and existing exascale nuclear physics applications pushing to higher physical fidelity, and consequently great computational cost, the paramount need for nuclear physics computing is enhanced access to exascale resources. Ideally, these resources would marry exaflop capabilities to sufficient memory bandwidth that our numerically intensive applications can deliver exascale performance. Essential nuclear physics simulations range from capability to capacity scales, along with specialized hardware systems, making both NERSC and the Leadership Computing Facilities essential partners in our work. With many areas of nuclear physics finding new and creative uses for machine learning and artificial intelligence (ML/AI), often as emulators trained on HPC-computed datasets, the nuclear physics community has considerable interest in ML/AI accelerators working in tandem with HPC resources. Similarly, as nuclear physics applications explore the tremendous potential to solve at least portions of our quantum mechanical problems using quantum computing, we see extraordinary possibilities in hybrid quantum-HPC computing.

The nuclear physics experimental program, and subsequent downstream analysis, have significant needs for forefront data capabilities and data analytics. The rapidly evolving capabilities of ML/AI are already impacting nuclear physics research, from accelerators, to experiment, to theory, and this impact is expected to accelerate in the near-term. Enabling this requires access to ML/AI-optimized hardware and integrating techniques with other domains and the private sector. Quantum information science, quantum sensing, and quantum computing, which are essential for addressing key research priorities in nuclear physics, require access to large-scale classical computing resources, for emulation, co-designing quantum hardware for nuclear physics needs, and are an integral component in quantum simulations, including hybrid simulations. Increased access to quantum computing hardware and emulation resources, for instance through the Oak Ridge LCF, Advanced Quantum Testbed, and cloud providers, is required. Similarly, integrating techniques with other domains and the private sector is essential.

Facilities

Electron-Ion Collider

Assessment of the potential to contribute to world-leading science in the next decade

The scientific foundation for the Electron-Ion Collider (EIC) was built over two decades. The EIC was a concerted effort by the nuclear science community supported by the NSAC Long Range Plans of 2002 and 2007, and a top recommendation of the 2015 and recent 2023 plan. The EIC addresses unique and compelling science as evidenced by a 2018 consensus study report of the National Academies of Science, Engineering and Medicine. The EIC, to be built in the United States, will elucidate the origin of visible mass in the universe and significantly advance accelerator science and technology as the first major particle collider to be constructed since the Large Hadron Collider in Europe. The EIC will provide unprecedented ability to "x-ray" protons and atomic nuclei and discover how the mass of everyday objects is dynamically generated by the interaction of quark and gluon fields inside protons and neutrons. How their mass and other properties emerge remains deeply mysterious. The advances in accelerator science and technology, detector technology, and computing that will come with the EIC are expected to bring strong societal benefits to medicine, national security, manufacturing and studying new materials, computational tools, and more. The EIC is expected to employ artificial intelligence and machine learning techniques across the facility, from accelerator and detector operations to data analysis. The EIC will enable scientific capabilities that are unique worldwide, drawing a large international interest. The EIC User Group currently has over 1500 members from 40 countries in six continents, with 47% of members from outside the United States. Multiple foreign agencies, including ones in Canada, Italy, France, the UK, and South Korea are in the final proposal phase for EIC in-kind contributions. The EIC will be a new world-leading DOE facility at the forefront of scientific discovery. The Subcommittee ranks the EIC as **(a) absolutely central** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

The EIC will be sited at Brookhaven National Lab (BNL) and constructed in partnership with Thomas Jefferson National Accelerator Facility (Jefferson Lab). Argonne National Lab, Fermilab, Lawrence Berkeley National Lab, Oak Ridge National Lab and SLAC all contribute to its construction, together with U.S. universities and numerous international partners. The EIC construction project is notionally envisioned to be completed in the first part of the next decade. The project received CD-0 in December 2019 and CD-1 in June 2021. It received $138M of Inflation Reduction Act funding in September 2022, which must be spent by 2027. In November 2023, a DOE Independent Project Review for CD-3A, the start of long-lead procurements, was held, with CD-3A approval granted March 28, 2024. The State of New York awarded $100M for the construction of EIC support buildings in February 2024. The construction of the EIC facility is timed to leverage the existing Relativistic Heavy Ion Collider (RHIC) infrastructure at BNL and highly trained professionals that are immediately available upon the successful planned conclusion of the RHIC science program in September 2025. The Jefferson Lab radio frequency and cryogenics workforce will become available in 2026 following the completion of work in support of accelerator projects at ORNL and SLAC. The R&D performed to date confirms the technical feasibility of the facility, enabling the project team to maintain progress on preliminary design in advance of establishing the performance baseline. Formal agreements for international in-kind contributions, notably those from Canada, Italy, and the UK, are in development. Statements of Interest were signed by the DOE and French agencies. Concerning readiness of the facility for construction, we rank the EIC in category **(a) ready to initiate construction**.

High-Rigidity Spectrometer

Assessment of the potential to contribute to world-leading science in the next decade

The High-Rigidity Spectrometer (HRS) will be the centerpiece experimental tool of the Facility for Rare-Isotope Beams (FRIB) fast-beam program, and it has been identified as a key instrument for FRIB in the 2023 LRP. The device will substantially increase FRIB's scientific reach and productivity, enabling experiments with beam intensities of few ions per second or less through the luminosity afforded by thick targets. The high magnetic rigidity of the HRS (8 T·m) will match the rigidities for which rare-isotope production yields at the FRIB fragment separator are maximum across the entire chart of nuclei and enable experiments with the most exotic, neutron-rich nuclei available at FRIB as well as for the planned upgrade FRIB400.

The HRS is divided into two segments: the High-Transmission Beam Line (HTBL) and the Spectrometer Section (SPS). HTBL transports rare-isotope beams from the Advanced Rare Isotope Separator (ARIS) fragment separator to the reaction target stationed at the entrance of SPS. The function of the SPS is to analyze the fast-moving reaction products created at the target. A wide variety of ancillary detector systems developed by the nuclear science community for experiments at FRIB will be used in combination with the HRS, including the Gamma-Ray Energy Tracking Array (GRETA) and the Modular Neutron Array (MONA-LISA).

The scientific program envisioned for the HRS is broad and addresses outstanding questions in nuclear structure, nuclear matter, and nuclear astrophysics. The HRS will transmit with nearly 100% efficiency isotopes that are traveling at velocities for which the rare-isotope production rate is optimal, allowing the ability to measure properties such as mass, charge, and velocity. In addition, at the higher velocities, the foils in the rare-isotope production target—in which reactions between isotopes take place—can be much thicker, greatly increasing the chances that a desired isotope reaction will occur. The combined effects of a higher rare-isotope beam intensity and the use of thicker target foils will greatly increase the sensitivity of the scientific program at FRIB by extending the scientific reach to neutron-rich isotopes by up to a factor of about 100. This will be beneficial for experiments with the most neutron-rich isotopes that have the highest potential for discovery and enabling forefront experiments not otherwise possible anywhere in the world. The Subcommittee assesses the project as **(b) important** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

The HRS has undergone numerous reviews since the release of the whitepaper in 2014 culminating in Critical Decision 1 (CD-1) approval in September 2021. The project has recently seen an increase in available workforce where FRIB design and engineering effort has been transferred from FRIB to HRS following the completion and commissioning of FRIB. Finalization of the HTBL design is nearing completion with a Critical Decision 2 (CD-2) project review scheduled in October 2024. In addition, approximately $30M in funds for the construction of the HRS have been obtained through the Inflation Reduction Act (IRA), which must be spent by the end of 2027. Completion of the HTBL will enable a portion of the envisioned physics program such as mass determination of exotic isotopes using the time-of-flight method. The remaining physics program will utilize the SPS, for which approximately 30% of the design is complete. It is estimated that the CD-2 review for SPS will take place in mid-2025, and assuming CD-2 approval, the remaining components of the SPS can be built and installed contingent on funding being made available to complete the project. The Subcommittee assesses the project as **(a) ready to initiate construction**.

Ton-Scale Neutrinoless Double-Beta Decay Campaign

Assessment of the potential to contribute to world-leading science in the next decade

The discovery of neutrinoless double-beta (0nubb) decay, a potential nuclear process in which two neutrons inside a single nucleus convert into two protons and two electrons, *but no neutrinos are emitted,* would unambiguously demonstrate that an excess of matter over antimatter can indeed be created in microscopic processes. This result would have profound consequences for our understanding of how the universe contains so much more matter than antimatter, and thus would be of great interest also to related fields such as particle physics, astrophysics and cosmology. The existence of 0nubb decay is intimately related to one of the most important questions in fundamental physics today: what is the physics responsible for the tiny but nonzero neutrino masses? We do not know the answer, but several potential mechanisms exist that make different predictions for another key question: are neutrinos Majorana fermions (i.e., are neutrinos their own antiparticles)? If neutrinos are Majorana fermions, then 0nubb decay can occur, and if it is ever observed, then neutrinos must be Majorana fermions.

Experiments to observe 0nubb decay are thus crucial and challenging. Our current knowledge of neutrino mass and nuclear theory indicates that ton-scale neutrinoless double beta decay experiments are poised to influence our understanding of neutrinos in a potentially decisive way. Since experimental evidence for such an extraordinarily rare process—a result that should earn a Nobel Prize—would demand confirmation, an observation in more than one isotope, each with significantly different detector uncertainties, is necessary. The proposed U.S. program consists of three experiments, fielding very different detection technologies and using three different isotopes: CUPID with ^{100}Mo, LEGEND-1000 with ^{76}Ge, and nEXO with ^{136}Xe. Observation in multiple isotopes is the first step towards unraveling the underlying physics of lepton number violation.

The 2023 NSAC LRP identified, as the highest priority for new experiment construction, that the U.S. lead an international consortium that will undertake a neutrinoless double-beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques. Hence the Subcommittee assesses the campaign as **(a) absolutely central** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

Technology demonstrators for several candidate isotopes have proven the principles required for successful next-generation ton-scale searches. The selected three experiments have undergone a rigorous DOE portfolio review and are actively preparing for the Critical Decision (CD) process. CUPID builds on the infrastructure developed for the demonstrator CUORE at Gran Sasso National Laboratory (LNGS) in Italy and leverages the expertise of the long-standing CUORE collaboration. CUPID has pioneered several technologies including successful operation of one of the largest mK dilution refrigerators. Hardware development for quantum computing is now driving advances in mK cryogenic technology and quantum sensing. The first phase of the LEGEND program, LEGEND-200, is now operating at LNGS. Recently, the collaboration was invited to prepare a full proposal to the NSF Midscale Research Infrastructure-2 program for LEGEND-1000. The nEXO experiment technology concept has been developed over the last decade and has been well documented. Recently, the nEXO project has successfully completed a series of external reviews for 10 of 11 subsystems. Overall, none of the three experimental designs have any significant scientific/engineering challenges to resolve before initiating construction, but isotope acquisition has been identified as a significant challenge in each case. The procurement chain for ^{100}Mo crystals and isotope has been established. However, a complete plan to navigate potential geopolitical complexities impacting supply chains and acquisition remains to be developed with international partners. The supply of enriched ^{76}Ge and underground-sourced argon have been established but identified as potential sources of schedule risk. Likewise, while a sufficient amount of xenon is produced industrially in the world and ^{136}Xe enrichment technology has been established in many countries, acquisition remains a schedule risk. Based on the above, the Subcommittee assesses that the campaign is **(a) ready to initiate construction**.

Project 8

Assessment of the potential to contribute to world-leading science in the next decade

The discovery of neutrino flavor transformations has demonstrated that neutrinos have nonzero masses and provided the first laboratory-based evidence of physics beyond the so-called Standard Model of fundamental interactions. While oscillation experiments are exquisitely sensitive to neutrino mass splitting and may reveal the spectrum mass ordering, Project 8 plans to directly measure the tritium beta decay spectrum in the vicinity of the end-point to directly access the neutrino mass scale m_β, relying solely on the principle of conservation of energy and momentum. A definitive measurement of the neutrino mass scale would reverberate across various disciplines, including high-energy physics and cosmology, and would shed light on scientific questions ranging from the neutrino mass generation mechanism to the impact of cosmological neutrinos on the large-scale structure of the universe. The current state-of-the-art measurement from KATRIN in Germany implies a 90% CL limit of $m_\beta < 800$ meV, with ultimate sensitivity of $m_\beta \sim 300$ meV by 2025, after which the technique employed by the experiment meets fundamental barriers that hinder further progress. The Project 8 experiment will exploit two major innovations. First, it will utilize Cyclotron Radiation Emission Spectroscopy (CRES), a scalable electron spectroscopy technique that has inherently sharp energy resolution and very low backgrounds. Second, it will develop an intense source of cold (mK), spin-polarized atomic tritium, using magnetic evaporative cooling in a beam, which also applies to other atoms or molecules with a magnetic moment. Beyond nuclear physics, an intense source of polarized atomic tritium is of interest to the atomic, molecular, and optical (AMO) physics community and could enable a number of fundamental physics studies, including precision spectroscopy and Bose-Einstein condensation in tritium. The combination of CRES and atomic tritium sources has the potential to reach almost an order of magnitude lower in sensitivity, or $m_\beta \sim 40$ meV at 90% C.L. This targeted level of sensitivity is particularly exciting, since it will be possible to determine the mass ordering of neutrinos by virtue of covering the inverted ordering scale. The experiment will also have a unique sensitivity to the existence of light sterile neutrinos at the eV scale, thus offering another opportunity for a major discovery. As of today, no other known technology has the potential to reach a neutrino mass scale of 40 meV. Hence the Subcommittee assesses Project 8 in category **(b) important** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

Project 8 plans to use two new technologies: CRES to measure tritium beta-decay electrons, and an atomic tritium source to eliminate the systematic uncertainties inherent to final states in molecular tritium decay. While a proof-of-principle of the CRES technique has been achieved and has provided a first upper limit on the neutrino mass ($m_\beta \leq 155$ eV) with less than a cubic centimeter of active volume and no background observed, the project is in the early stages of conceptual design. The path forward involves a phase of significant R&D, Phase III, with two efforts to be pursued in parallel: (a) the demonstration that CRES scales to volumes of at least about 10 m^3 by performing a U.S.-based (molecular) tritium endpoint experiment with neutrino mass sensitivity comparable to KATRIN; (b) the development of a large and pure source of tritium atoms. The latter effort will be pursued by German collaborators. The ultimate demonstration of the feasibility of Project 8 will be a pilot-scale experiment using both CRES and an atomic-tritium source at the 10 m^3 scale. For this Phase III, while the mission and technical requirements are clearly defined, there are still significant technical challenges to resolve before initiating construction, identified as a strategic opportunity as stated above. The full scientific goal of Project 8 will be achieved in Phase IV, which will reach sensitivity down to 40 meV. Technically, this can be reached by assembling ten copies (nine new) of the atomic-tritium pilot experiment at the 10 m^3 scale that would result from Phase III. Project 8 Phase IV crucially depends on the outcome of the demonstrators to be developed in Phase III. At this time, there is not sufficient information to assess the full scope and cost of the Phase IV experiment. Based on this, the Subcommittee assesses Project 8 Phase IV in category **(c) mission and technical requirements not yet fully defined**.

Facility for Rare Isotope Beams Energy Upgrade

Assessment of the potential to contribute to world-leading science in the next decade

An energy upgrade of the Facility for Rare Isotope Beams (FRIB) linear accelerator to 400 MeV/nucleon for uranium (FRIB400) will expand the already broad scientific reach of FRIB to encompass the full range of science envisioned by the scientific community and articulated in NSAC Long Range Plans and studies by the National Academy of Sciences. The need for the upgrade is timely due to recent astronomical observations. Scientific gains from FRIB400 above those to be realized at FRIB are impactful and diverse: (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 can be created and studied at up to twice saturation density, critical for multi-messenger astrophysics; (iii) the luminosity will be increased by up to two orders of magnitude for spectroscopy in key regions of the nuclear chart; and (iv) nuclear reactions can be performed in an energy regime optimal for reaction models. FRIB400 will increase the yield of many harvested isotopes by a factor of 10, advancing applications of rare isotopes and atomic/molecular electric-dipole-moment (EDM) measurements with octupole-deformed rare isotopes, which offer promising opportunities to discover sources of time-reversal violation beyond the Standard Model, an endeavor of interest to the high-energy physics community. After the upgrade, FRIB will eclipse the Radioactive Isotope Beam Factory (RIBF) facility at RIKEN in Japan in energy as well as beam intensity.

A state-of-the-art accelerator to produce beams of radioactive ions from a 400 MeV/nucleon uranium beam was the highest priority for new construction in the 2002 LRP. By 2006 it became clear that the $1.1B cost was outside of what could be envisioned at that time. After an NSAC study there was a recommendation for the DOE to proceed with a 200 MeV/nucleon machine, which became the design constraint for FRIB. FRIB was the highest priority for new construction in the 2007 Long Range Plan for Nuclear Science. When FRIB was baselined, the government approved that the FRIB tunnel be designed and built to be upgradable to achieve 400 MeV/nucleon for uranium. FRIB was constructed on budget and ahead of schedule, and it delivered first beam in May 2022. The science from that first experiment was published in Physical Review Letters in November 2022. An energy upgrade to 400 MeV/nucleon will achieve the capabilities envisioned in the 2002 LRP.

The science opportunities afforded by FRIB400 and its enabling accelerator technology feature throughout the 2023 LRP. FRIB400 is explicitly listed in the Executive Summary as an opportunity that advances discovery science. The rare isotope beam-intensity increase associated with FRIB400 will benefit all experiments, thus serving a base of more than 1800 registered users. The Subcommittee assesses FRIB400 as **(b) important** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

Space is reserved in the FRIB tunnel for the 11 cryomodules of FRIB400, enabling 400 MeV/nucleon energy for uranium and higher energies for lighter ions. The technology has been proven, prototypes have been tested, and the team to build FRIB400 is in place. The upgrade can be implemented in stages during regular shutdowns with minimal interruption of the FRIB science program. At each stage, the gain in primary beam energy will translate into increased science potential. During the ongoing FRIB capability ramp-up, longer shutdowns are planned that could be used to install the FRIB400 infrastructure. The FRIB fragment separator and the beam distribution to key detector systems are well matched to the upgrade.

The team that delivered the FRIB project will deliver the FRIB400 project. The FRIB400 β=0.65 superconducting resonators attained world-record accelerating gradients exceeding the performance requirements for FRIB400. Multiple industrial partners are qualified to mass produce the needed accelerator components. Since 2017, a total of 22 technical reviews have been conducted on the design of accelerator subsystems for FRIB400. At this time all technical uncertainties are believed to have been resolved and cost estimates have been obtained for major procurements such as the niobium material and the cavity mass production. However, until the DOE embarks on a full CD-0 and then CD-1 review, information on the cost and schedule uncertainties is not available. The Subcommittee assesses FRIB400 in category **(a) ready to initiate construction**.

Solenoidal Large Intensity Device

Assessment of the potential to contribute to world-leading science in the next decade

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is focused on studying how the properties of hadrons, such as protons and neutrons, arise from their quark and gluon building blocks. In addition, precision measurements of electron-nucleus scattering observables that differ slightly under parity (mirror) transformation provide an exquisite test of the weak interactions mediated by the neutral Z boson and probe the existence of possible new forces, with implications for particle physics.

The Solenoidal Large Intensity Device (SoLID) is a large-acceptance spectrometer planned for Jefferson Lab Hall A. The physics program of SoLID consists of three avenues of scientific investigation: (i) semi-inclusive deep-inelastic scattering (SIDIS) to provide multidimensional imaging of the structure of the nucleon, (ii) threshold production of the J/Ψ meson to understand the gluonic field contribution to the proton structure and proton mass, and (iii) parity-violating deep-inelastic scattering (PVDIS) to test the Standard Model of particle physics in the electron-quark sector. The uniqueness of SoLID is its capacity to carry out these measurements at unprecedented luminosities and rates, essential for the high statistics required by these precision measurements. Specifically, the luminosity with the large-acceptance SoLID spectrometer will reach 10^{37} cm^{-2} s^{-1} for the SIDIS and J/Ψ configurations, with a figure-of-merit (acceptance times luminosity) two orders of magnitude or more higher than other currently available or planned facilities. These measurements will primarily cover the kinematic regime relevant to the valence quark structure of the nucleon and be complementary to planned measurements at the EIC that investigate contributions of sea quarks and gluons to nucleon structure. The luminosity of the SoLID PVDIS program will reach 10^{39} cm^{-2} s^{-1}, which cannot be realized anywhere else and will provide precision measurements of the electron-quark couplings. The science that is enabled by the SoLID detector is critically important to realizing the full potential of the upgraded 12 GeV beam energy and high current capability at Jefferson Lab. The Subcommittee thus assesses SoLID as **(b) important** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

SoLID will utilize an existing solenoid magnet, from the former CLEO-II experiment, which has been relocated to Jefferson Lab and undergone initial cold tests successfully. The detector components of SoLID are all based on known technologies and consist of gas electron multipliers for tracking, gas Cherenkov detectors, scintillator paddle detectors, and electromagnetic calorimeters for particle identification. A preliminary conceptual design report (pre-CDR) was initially written in 2014 and was further refined three times, with the most recent (2019) version submitted to the DOE Office of Nuclear Physics in 2020 as part of the SoLID MIE proposal.

SoLID underwent three Jefferson Lab Director's reviews, with the most recent in 2021. These reviews and subsequent DOE-supported pre-R&D activities greatly refined and solidified the pre-conceptual design. Cost estimations were performed and reviewed for each version of the pre-CDR, including a full cost exercise in 2019 that was updated in 2023. The estimated costs have been stable over these cost estimations since 2014 after accounting for realistic escalations. A DOE Science Review was conducted in March 2021, and the committee provided positive feedback on both the science and the design at the close-out.

While all detector systems of SoLID are designed based on existing technology, the high radiation, high backgrounds, and high-rate environment of Jefferson Lab present unique challenges. In the past four years, prototypes were produced for all detector subsystems. Both the Cherenkov and the calorimeter prototype modules underwent beam tests at Jefferson Lab that mimic the actual running conditions of SoLID. All detector subsystems are found to be operational under realistic running conditions, with viable solutions available for the detector readout and the data acquisition systems. These pre-R&D activities demonstrate that the design choices of all SoLID subsystems operate well in the expected high-luminosity environment.

At this time there are no known significant engineering or scientific challenges to be resolved before initiating construction. However, until the DOE embarks on a full CD-0 and then CD-1 review, information on the cost and schedule uncertainties is not available. The Subcommittee assesses SoLID in category **(a) ready to initiate construction**.

Electron-Ion Collider Detector II

Assessment of the potential to contribute to world-leading science in the next decade

The science case for a second detector (DetII) located at interaction region 8 (IR8) at the Electron-Ion Collider (EIC) is broad and overlaps significantly with the science motivation developed for the EIC and endorsed by the National Academy of Sciences (NAS). This motivation includes fundamental questions about the origin of the proton's spin and mass, the characteristics of the "glue" that binds quarks inside of nucleons, and the nature of very dense gluon systems in nuclei.

While the ePIC Detector, located at interaction region 6 (IR6) at the EIC, is designed to address the science program described in the NAS report, a second detector will allow for enhanced capabilities in selected sectors. Examples include a stronger magnetic field for increased tracking resolution in the kinematic region crucial for exploring the predicted nonlinear effects in the gluon structure of nuclei, a topic that was highlighted as high discovery potential in the NAS report. The addition of a muon detector subsystem at DetII, currently not planned for the ePIC detector package, will allow the EIC to explore heavy flavor physics via complementary decay channels while also opening doors to new channels in proton tomography and physics beyond the Standard Model of particle physics. Finally, the implementation of a secondary focus into the beam optics of IR8 will enable a novel program focused on the 3D quark-gluon structure of nuclei and the phenomenology of nuclear target fragmentation by allowing for the direct detection of scattered nuclear fragments in the far-forward region. The secondary focus would require advancements in the design of strong, large-aperture magnets, a concrete example of how the EIC, and the second detector specifically, could motivate new developments in accelerator physics and technology. Besides providing these new opportunities and the reduction of systematic uncertainties when combined with precision results from ePIC, only a second detector allows for mutual confirmation of results, a crucial component of discovery science at a facility that is unique worldwide. Two detectors will also expand the opportunities for a new generation of scientists and encourage technological development and innovation by fostering between the two collaborations a healthy and friendly competition, which provides the most fertile ground for the emergence of the best new ideas. The Subcommittee assesses EIC DetII in category **(b) important** in its potential to contribute to world-leading science in the next decade.

Assessment of readiness for construction

The timeline for a second experiment is important. The programs at IR8 will follow ePIC by several years, allowing for the timely validation of flagship measurements and the exploration of surprising new results. This delayed time frame is being used to pursue advances in detector technologies via the current EIC-related generic detector R&D program managed by Jefferson Lab. In the spring of 2022 the EIC Detector Proposal Advisory Panel, an international committee of detector experts and theorists assembled to review the detector proposals submitted for IR6, noted in their report, "There is significant support in the community and from the panel for a second general-purpose detector system to be installed in IR8 when resources are available." Capitalizing on this momentum, the EIC User Group formed the 2nd Detector and IR8 Working Group in the summer of 2022 and charged them with engaging the broader community to develop a unified concept for a second detector at IR8. This Working Group is in the process of refining the science case for a second detector and plans to engage in the DOE critical decision process within the next five years. Considering this status, the Subcommittee assesses the readiness for construction in category **(c) mission and technical requirements not yet fully defined**.

Appendix A

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

December 1, 2023

To: CHAIRS OF THE OFFICE OF SCIENCE FEDERAL ADVISORY COMMITTEES:
Advanced Scientific Computing Advisory Committee
Basic Energy Sciences Advisory Committee
Biological and Environmental Research Advisory Committee
Fusion Energy Sciences Advisory Committee
High Energy Physics Advisory Panel
Nuclear Science Advisory Committee

The Department of Energy's Office of Science (SC) has envisioned, designed, constructed, and operated many of the premiere scientific research facilities in the world. More than 38,000 researchers from universities, other government agencies, and private industry use SC User Facilities each year—and this number continues to grow.

Stewarding these facilities for the benefit of science is at the core of our mission and is part of our unique contribution to our Nation's scientific strength. It is important that we continue to do what we do best: build facilities that create institutional capacity for strengthening multidisciplinary science, provide world class research tools that attract the best minds, create new capabilities for exploring the frontiers of the natural and physical sciences, and stimulate scientific discovery through computer simulation of complex systems.

To this end, I am asking the SC advisory committees to look toward the scientific horizon and identify what new or upgraded facilities will best serve our needs in the next ten years (2024-2034). More specifically, I am charging each advisory committee to establish a subcommittee to:

1. Consider what new or upgraded facilities in your disciplines will be necessary to position the Office of Science at the forefront of scientific discovery. The Office of Science Associate Directors have prepared a list of proposed projects that could contribute to world leading science in their respective programs in the next ten years. The Designated Federal Officer (DFO) will transmit this material to their respective advisory committee chairs. The subcommittee may revise the list in consultation with their DFO and Committee Chair. If you wish to add projects, please consider only those that require a minimum investment of $100 million. In its deliberations, the subcommittee should reference relevant strategic planning documents and decadal studies.

2. Deliver a short letter report that discusses each of these facilities in terms of the two criteria below and provide a short justification for the categorization, but do not rank order them:

    a. **The potential to contribute to world-leading science in the next decade.** For each proposed facility/upgrade consider, for example, the extent to which it would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research and especially whether the facility will address needs of the broad community of users including those whose research is supported by other Federal agencies; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the (sometimes many) scientific communities that use the facility. **Please place each facility or upgrade in one of four categories: (a) absolutely central; (b) important; (c) lower priority; or (d) don't know enough yet.**

    b. **The readiness for construction**. For proposed facilities and major upgrades, please consider, for example, whether the concept of the facility has been formally studied; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to date to assure technical feasibility of the facility; the extent to which the cost to build and operate the facility is understood; and site infrastructure readiness. **Please place each facility in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; or (c) mission and technical requirements not yet fully defined.**

Many additional criteria, such as expected funding levels, are important when considering a possible portfolio of future facilities, however, for this assessment I ask that you focus your report on the two criteria discussed above.

I look forward to hearing your findings and thank you for your help with this important task. I appreciate receiving your final report by May 2024.

Sincerely,

Asmeret Asefaw Berhe
Director, Office of Science

Appendix B

2023 DOE/NSF Nuclear Science Advisory Committee Facilities Charge

In response to Dr. Berhe's December 2023 Facilities Charge, Nuclear Physics is providing the following list of projects for consideration by the subcommittee.

Electron-Ion Collider (EIC)

Total Project Cost (TPC) range: $1.7B to $2.8B

The EIC will be located at Brookhaven National Laboratory, which will lead its construction in partnership with Thomas Jefferson National Accelerator Facility (TJNAF). ANL, LBNL, ORNL and LANL will also contribute to its construction, notionally envisioned to complete in the first part of the next decade. The EIC will provide unprecedented ability to "x-ray" the proton and discover how the mass of everyday objects is dynamically generated by the interaction of quark and gluon fields inside protons and neutrons. The EIC accomplishes this by colliding highly polarized electrons with a variety of ion species at high center-of-mass energy, and with high luminosity. Understanding how the macroscopic properties of the spin and mass of protons and neutrons are generated is key to addressing an outstanding grand challenge problem of modern physics: how quantum chromodynamics, the theory of the strong force, explains all strongly interacting matter in terms of points like quarks interacting via the exchange of gluons. The EIC is envisioned to be international in character. The EIC User Group actively working to develop concepts for the EIC detector, ePIC, comprises 1400 users from 277 institutions in 36 countries.

Current status: CD-1 achieved June 2021.

High-Rigidity Spectrometer (HRS)

Total Project Cost (TPC) range: $85M to $111M

The HRS will allow experiments at FRIB using beams of rare isotopes to be carried out at the maximum fragmentation or in-flight fission beam intensities, providing critical isotopes not available otherwise. The existing spectrometer available at FRIB has a limited bending capability, which limits the fluences achievable in experiments with fast rare isotope beams. The HRS removes this limitation by doubling the bending capability and matching the rigidities at which the most neutron-rich rare isotopes produced at FRIB—those of greatest interest for understanding nucleosynthesis in the cosmos— will have the highest production rate. This gain in rare isotope production rate increases the scientific potential of state-of-the-art detector instrumentation which the research community places high priority on, such as the Gamma-Ray Tracking Array (GRETA), to be used in conjunction with the HRS.

Current status: CD-1 achieved September 2020.

Ton-Scale Neutrinoless Double-beta Decay (TS-NLDBD)

Total Project Cost (TPC) range: $350M to $500M

Projects planned under a TS-NLDBD experiment program will instrument a large volume of a specially selected isotope to detect neutrinoless double beta decay ($0\nu\beta\beta$). The observation of NLDBD would demonstrate that the neutrino is its own antiparticle and elucidate the mechanism, completely unknown at present, by which the mass of the neutrino is generated. The observation would have major implications for the present-day matter/anti-matter asymmetry which has perplexed modern physics for decades and could reveal unknown particle states such as a conjectured heavy, right-handed neutrino.

The goal of a next generation ton-scale experiment is to reach a lifetime limit of a few counts in 10^{28} years. Three technologies (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND-1000), Next Enriched Xenon Observatory (nEXO), and Cryogenic Underground Observatory for Rare Events with Particle Identification (CUPID)) employing different isotopes to ensure a definitive outcome as a result of this scientific campaign are poised to reach this limit withing a 10-year measurement period. Working with the international community to deploy multiple experiments is important for contemporaneous verification as the best chance for unambiguous discovery. To be viable, the offshore international community will need to undertake at least a 50% share of the resources needed for this campaign.

Current status: CD-0 achieved November 2018.

Project 8

Total Project Cost (TPC): TBD

Project 8 will measure the absolute value of the neutrino mass by precisely measuring the energies of beta-decay electrons in the high-energy tail of the spectrum of tritium beta decays. Knowing the highest possible beta-decay energy determines the lower limit on the neutrino mass by simple conservation of momentum and energy in a three-body decay. The excitement is that Project 8 is using a new method of electron spectroscopy developed by PNNL and the University of Washington, Cyclotron Radiation Emission Spectroscopy, which measures the frequency of the cyclotron motion of electrons in a constant magnetic field to achieve a precise measurement of the energy. The ultimate science goal of Project 8 will be the use atomic tritium to measure the neutrino mass down to a limit of approximately 40 meV, about 20 times better than the current world limit.

Current status: Not an ongoing project, science review held July 2023.

Facility for Rare Isotope Beams Energy Upgrade (FRIB400)

Total Project Cost (TPC): TBD

The FRIB400 will extend the tremendous discovery potential of FRIB by realizing significant gains in isotope yields, nearly doubling the scientific reach of FRIB along the neutron dripline and bringing access to more nuclei relevant for the r process and neutron-star crust processes thought to be prime drivers of heavy element production in the cosmos. FRIB400 is an energy upgrade of the FRIB linear accelerator from 200 MeV/nucleon to 400 MeV/nucleon for uranium and to higher energies for lighter ions. Space was provided in the conceptual design of the FRIB tunnel for the proposed energy upgrade, which can be implemented with minimal interruption of the FRIB science program. The unlocked science potential includes creating dense nuclear matter at up to twice normal nuclear density, which is critical for multi-messenger astrophysics.

Current status: Not an ongoing project, white paper updated February 2023.

Solenoid Large Intensity Device (SoLID)

Total Project Cost (TPC): TBD

The SoLID detector will exploit the full potential of the CEBAF 12 GeV upgrade, enabling measurements in quantum chromodynamics and electroweak physics. SoLID is a large acceptance forward scattering spectrometer with full azimuthal angular coverage capable of handling high luminosities with a variety of polarized and unpolarized targets. The detector's science programs will focus on the three-dimensional imaging of the nucleon in a kinematic region complementary to the EIC, beyond standard-model searches for new physics, and exploration of gluonic forces.

Current status: Not an ongoing project, science review held March 2021.

Electron-Ion Collider (EIC) Detector II

Total Project Cost (TPC): TBD

The EIC project currently includes one large-acceptance detector, ePIC, that will capture most of the particles scattering from collisions of electrons and ions in all directions and at a wide range of energies. Detector II for the EIC will be complementary to the ePIC project detector, will focus its capabilities on full exploration of phenomena discovered in the first phase of ePIC research, and will capitalize on the possibility of a secondary focus. Multiple detectors will expand scientific opportunities building on the discoveries already made with the ePIC detector, drawing a more vivid and complete picture of the science, providing an independent confirmation for discovery measurements, and adding critical statistics to systematics-limited measurements the EIC expects to perform.

Current status: Not an ongoing project, first international workshop held May 2023.

1 EXECUTIVE SUMMARY

Nuclear science is the investigation of how protons and neutrons are formed from elementary particles and how the forces between those particles produce both nuclei and the vast variety of nuclear phenomena that occur in the universe. It has evolved into a broad field that addresses profound scientific questions: Where does the mass of visible matter come from? How do stars ignite, live, and die? How do nuclei illuminate the search for new laws of nature? This science points the way to using nuclei to build new technologies that benefit society.

The 2015 Nobel Prize in physics was shared by nuclear physicists Art McDonald and Takaaki Kajita for the discovery of neutrino oscillations, which confirmed that neutrinos have mass. Our progress on big questions like this one since 2015 has been remarkable owing to new experimental tools, theoretical breakthroughs, powerful computational techniques, and the talented people who make these innovations possible. Focusing on these new tools, the Facility for Rare Isotope Beams (FRIB) at Michigan State University is already producing exciting results on decays of never-before-produced isotopes a year after it was completed on time and on budget. The energy upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) was also completed on schedule and on budget—new data from this facility are revealing the spectrum, structure, and dynamics of protons, neutrons, nuclei, and mesons. On the theory front, we can now calculate the distribution of quarks inside the proton from first principles. The implementation of artificial intelligence (AI) and machine learning (ML) techniques has led to improved data analysis and increased efficiency in running experiments and theoretical calculations.

The impact of nuclear science goes beyond expanding the frontiers of knowledge about matter in the universe. We simultaneously develop a STEM workforce that advances the security, technology, health, and wealth of our nation. Some connections are obvious. Expert scientists trained to work with radioactive nuclei are in demand in nuclear security arenas and are highly sought after by various government agencies and private industries. Graduate students and postdoctoral fellows (postdocs) obtain extensive computational, modeling, and data science skills that are similarly in high demand. Less obvious but equally important is the connection between these trained scientists and success in other professions, including medicine, energy, and entrepreneurial pursuits. The workforce that enables discovery in nuclear science also makes breakthroughs in technologies with tremendous impact on the nation's economic advancement.

1.1 LONG RANGE PLAN PROCESS AND HISTORY

The nuclear science community has a proud tradition of producing thoughtful and impactful Long Range Plans, dating back to 1979. The previous Long Range Plan, *Reaching for the Horizon*, was published in 2015. The nuclear science community has proven to be a reliable steward of public funds. We work hard to reach consensus and articulate our priorities for the science in the coming decade. Much of the vision captured in the 2015 Long Range Plan has been implemented, and we are witnessing the fruits of those investments.

Our planning process involves the entire community from the beginning. The Nuclear Science Advisory Committee (NSAC) received the charge to develop a new Long Range Plan (Appendix A) from the US Department of Energy (DOE) Office of Science (SC) and the National Science Foundation (NSF) in July 2022. The American Physical Society Division of Nuclear Physics (DNP) organized three scientific town meetings that drew participation from more than 1,200 people (Appendix B). White papers were written based on the town meetings to provide input to the long-range planning process. Furthermore, smaller groups and collaborations met and submitted additional white papers on new research and educational opportunities for the next decade. All these white papers can be found on the NSAC Long Range Planning website, NuclearScienceFuture.org. A broad committee of 60 community members and two international observers (Appendix C) was formed to consider the input, debate the priorities, and choose the recommendations presented here (Appendix D includes the agenda of the July 2023 resolution meeting).

1.2 THE SCIENCE QUESTIONS

Nuclear science addresses some of the outstanding challenges to modern physics, including the properties and limits of matter, the forces of nature, and the evolution of the universe:

- How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?
- How do the rich patterns observed in the structure and reactions of nuclei emerge from the interactions between neutrons and protons?
- What are the nuclear processes that drive the birth, life, and death of stars?

- How do we use atomic nuclei to uncover physics beyond the Standard Model?

These questions are addressed by thousands of nuclear scientists working in experimental, theoretical, and computational investigations. Anchoring this world-leading program are the four national user facilities, each with unique capabilities for addressing our science questions: the Argonne Tandem Linac Accelerator System (ATLAS), CEBAF, FRIB, and the Relativistic Heavy Ion Collider (RHIC). A consortium of 13 university-based accelerator laboratories, known collectively as the Association for Research at University Nuclear Accelerators (ARUNA) laboratories, provide additional capability for cutting-edge experiments while training the next-generation scientists in the tools and techniques of nuclear science. Our work is done in small and large collaborations across the country, connecting theoretical and experimental researchers at universities and national laboratories in a dynamic and exciting enterprise that leads to scientific discovery. Our progress on these and other intriguing questions since the last Long Range Plan—and the many opportunities for the future—are covered in this plan. We describe some of the many technological and computational innovations that drive our field and lead to considerable benefits to society. Central to this work are the people: we highlight the process of training nuclear scientists and how they go on to contribute to our nation in many areas.

Our vision for the future builds on the ongoing, world-leading US program in nuclear science, which includes

- Unfolding the quark and gluon structure of visible matter and probing the Standard Model at the 12 GeV CEBAF facility.
- Exploring the nature of quark–gluon matter and the spin structure of the nucleon at the RHIC facility and through leadership across the heavy ion program at the Large Hadron Collider (LHC).
- Making breakthroughs in our understanding of nuclei and their role in the cosmos through research at the nation's low-energy user facilities, ATLAS, the newly constructed FRIB, the ARUNA laboratories, and key national laboratory facilities.
- Carrying out a targeted program of experiments, distributed across the United States, that reaches for physics beyond the Standard Model through rare process searches and precision measurements.
- Explaining how data gathered in these endeavors are connected and consistent through theory and computation. Nuclear theory motivates, interprets, and contextualizes experiments, opening up fresh research vistas.

Here are the recommendations of the 2023 Long Range Plan.

RECOMMENDATION 1

The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

This recommendation requires

- Increasing the research budget that advances the science program through support of theoretical and experimental research across the country, thereby expanding discovery potential, technological innovation, and workforce development to the benefit of society.
- Continuing effective operation of the national user facilities ATLAS, CEBAF, and FRIB, and completing the RHIC science program, pushing the frontiers of human knowledge.
- Raising the compensation of graduate researchers to levels commensurate with their cost of living—without contraction of the workforce—lowering barriers and expanding opportunities in STEM for all, and so boosting national competitiveness.
- Expanding policy and resources to ensure a safe and respectful environment for everyone, realizing the full potential of the US nuclear workforce.

Nuclear science is an ecosystem in which facility operations and research at laboratories and universities by senior investigators, technical staff, postdocs, and students work together to drive progress on the forefront science questions discussed above and throughout this Long Range Plan. A healthy workforce is central not only to these scientific goals but also to the nation's security, technological innovation, and prosperity.

Next, we reaffirm the exceptionally high priority of the following two investments in new capabilities for nuclear physics. The Electron–Ion Collider (EIC), to be built in the United States, will elucidate the origin of visible matter in the universe and significantly advance accelerator technology as the first major new advanced collider to be constructed since the LHC. Neutrinoless double beta decay experiments have the potential to dramatically change our understanding of the physical laws governing the universe.

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.

The importance of the physics being addressed by neutrinoless double beta decay has resulted in worldwide excitement and has catalyzed the international cooperation essential to carrying out a successful campaign. An extraordinary discovery of this magnitude requires multiple experiments using different techniques for a select set of isotopes. Such measurements demand unprecedented sensitivity and present unique challenges. Since the 2015 Long Range Plan, the US-led CUPID, LEGEND, and nEXO international collaborations have made remarkable progress with three distinct technologies. An independent portfolio review committee has deemed these experiments ready to proceed now.

Neutrinoless double beta decay is sensitive to new physics spanning very different scales and physical mechanisms. The identification of the underlying physics will pose a grand challenge and opportunity for theoretical research. An enhanced theoretical effort is an integral component of the campaign and is essential for understanding the underlying physics of any signal.

RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

Protons and neutrons are composed of nearly massless quarks and massless gluons, yet as the building blocks of atomic nuclei they make up essentially all the visible mass in the universe. Their mass and other properties emerge from the strong interactions of their relativistic constituents in ways that remain deeply mysterious. The EIC, to be built in the United States, is a powerful discovery machine, a precision microscope capable of taking three-dimensional pictures of nuclear matter at femtometer scales. These images will uncover how the characteristic properties of the proton, such as mass and spin, arise from the interactions between quarks and gluons, and how new phenomena and properties emerge in extremely dense gluonic, nuclear environments.

The EIC will be a unique, large-scale, high-luminosity electron–hadron collider and the only new major advanced collider to be built in the world in the next decade. It will be capable of colliding high-energy beams of polarized electrons with heavy ions, polarized protons, and polarized light ions. The EIC will be constructed on the current site of RHIC, led by a partnership between Brookhaven National Laboratory (BNL) and Jefferson Lab. The EIC was put forward as the highest priority for new facility construction in the 2015 Long Range Plan. Since then, the EIC was launched as a DOE project in 2019, and the conceptual design was approved in 2021. Its expeditious completion remains the highest priority for facility construction for the nuclear physics community.

The EIC facility design takes advantage of significant advances in accelerator and detector technologies, substantial investments in RHIC, and the unique expertise at BNL and Jefferson Lab, fulfilling the requirements of the 2018 National Academy of Sciences (NAS) report. The EIC's compelling, unique scientific opportunities and cutting-edge technologies are attracting physicists worldwide, and international engagement and contribution are important to the collider's realization and the success of the EIC science. Together with ePIC, the general-purpose, large-acceptance EIC detector, the EIC will maintain US leadership at the frontiers of nuclear physics and accelerator science technology. Many applications in industry, medicine, and security use particle accelerator and detector technologies: leading-edge accelerator and detector technology developments at EIC will have broad impact on these sectors.

To achieve the scientific goals of the EIC, a parallel investment in quantum chromodynamics (QCD) theory is essential, as recognized in the 2018 NAS report. Progress in theory and computing has already helped to drive and refine the physics program of the EIC. To maximize the scientific impact of the facility and to prepare for the precision expected at the EIC, theory must advance on multiple fronts, and new collaborative efforts are required.

RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Today's investments enable tomorrow's discoveries, with corresponding benefits to society. We underscore the importance of innovative projects and emerging technologies to extend discovery science, which plays a unique role in supporting national needs.

1.3 STRATEGIC OPPORTUNITIES

Strategic investments in forward-thinking projects and cross-cutting opportunities are important to ensure that the field continues to advance. They enable capitalization on emerging technologies and help ensure that the United States continues to maintain competitiveness and leadership throughout the next decade.

1.3.1. Opportunities to advance discovery

Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include the 400 MeV/u energy upgrade to FRIB (FRIB400), the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab, targeted upgrades for the LHC heavy ion program, emerging technologies for measurements of neutrino mass and electric dipole moments, and other initiatives that are presented in the body of this report.

Future advances in nuclear physics rely upon a vibrant program of detector and accelerator R&D, pushing for instance the current limits on detector sensitivity and on accelerator beam transport technology. R&D for novel nuclear physics detector and accelerator ideas influence fields such as medicine and national security. Such developments must continue.

1.3.2. Cross-cutting opportunities

1.3.2.1. Emerging technologies: computing and sensing

Nuclear physics is benefiting from and contributing to advances in quantum information science and technology (QIST) through research in quantum sensing and simulation. Creation of a multi-institutional effort such as the Nuclear Physics Quantum Connection will further accelerate mutually beneficial advances in nuclear physics and QIST.

Optimizing scientific discovery from rich experimental and computational data sets produced in nuclear physics research requires utilizing AI and ML technologies. Support for a coordinated effort to integrate AI/ML technologies into the nuclear physics research programs will accelerate discoveries.

High-performance computing (HPC) has led to remarkable scientific progress for nuclear physics, enabled in part by collaboration with computational scientists and applied mathematicians through the DOE Scientific Discovery through Advanced Computing (SciDAC) and NSF Cyberinfrastructure for Sustained Scientific Innovation programs. As we enter the era of exascale computing, with increasing numbers of communities within nuclear physics poised to take advantage of HPC, enhanced support will maximize scientific progress.

1.3.2.2. Multidisciplinary centers

The tremendous opportunities in the era of multi-messenger astronomy require nuclear science for interpretation. Multidisciplinary collaborative centers built around nuclear experiment and theory will expedite discoveries and allow the field of nuclear science to lead the quest to understand the cosmos through novel observations.

1.3.2.3. Nuclear data

Nuclear data from the nuclear physics community is important for medicine, energy, national security, nonproliferation, and space exploration. We endorse collaboratively funded projects that leverage modest investments to address some of the most important challenges and opportunities facing society.

1.4 INTERAGENCY COORDINATION AND COLLABORATION

The nuclear physics community has well-established and crucial partnerships with many federal science agencies. DOE and NSF work closely together to support broad aspects of nuclear science and have a particularly important collaboration in driving the emerging and cross-cutting fields of QIST, AI/ML, and HPC. These and other cross-cutting fields also provide connections and scientific opportunities with several other agencies. Examples include intersections with the National Institute of Standards and Technology (NIST) on quantum sensor technologies and strong synergies with the US Department of Defense and the National Institutes of Health (NIH) related to accelerator and detector science in nuclear physics. Our community has long been a leader in using HPC and is now adopting and advancing AI/ML methods to address multiple challenges in nuclear science. These innovations offer new opportunities for collaboration across all science agencies that will further advance the nation's entire science mission.

To strengthen interagency ties, the DOE Office of Nuclear Physics (NP) has initiated a new set of outreach activities to coordinate nuclear physics research in support of national needs. Since the last Long Range Plan, DOE and NIH launched a continuing series of workshops and webinars to explore multiple areas of mutual interest and opportunities to advance both communities. As an important example, in 2017 DOE NP formed a Nuclear Data Interagency Working Group (NDIAWG) and runs an annual series of Workshops on Applied Nuclear Data Activities (WANDA) with federal and private-sector partners to identify and address outstanding nuclear science needs. In the last 6 years the NDIAWG, through several funding opportunity announcements, has supported $50 million of collaborative experimental, modeling, and theoretical projects to address these needs using DOE NP and non-NP facilities and personnel. Many of these activities are described in the US Nuclear Data Program reports prepared by NSAC and released in April 2023. DOE NP also launched the highly successful DOE Isotope R&D and Production program (DOE IP) that has resulted in the availability of new isotopes for medicine, industry, and research. DOE NP and IP maintain a close working relationship in order to ensure the availability of important radioisotopes. Other examples of the impact of nuclear science and technology on other agencies are included throughout this plan.

1.5 WORKFORCE

Underpinning the advances in nuclear research and development is a scientifically trained workforce. People are essential to accomplishing the goals in all areas of physics outlined in this Long Range Plan. Building the next-generation STEM workforce requires strategic efforts to grow and maintain interest in science and the skills needed to pursue it. The excitement of scientific discovery must be encouraged early in a person's life and nourished throughout their career. Nuclear science education truly begins when undergraduate students are exposed to researchers at universities and national laboratories across the world, for example through summer programs (e.g., the NSF Research Experience for Undergraduates [REU] program or the DOE Science Undergraduate Laboratory Internships [SULI]) or research opportunities with faculty during the academic year. These experiences influence their career choices and decisions to pursue graduate studies. Graduate researchers learn skills that are critical to the scientific enterprise, including hands-on laboratory skills, the ability to work with large datasets, project management, and scientific communication. These and other skills are used in broad areas of physics and can be additionally applied to a wide variety of industries and government agencies. The recommendations and initiatives described in Chapter 8 discuss, in greater detail, the needs for a STEM-ready workforce and steps that can be taken to nurture and sustain it. Central to our proposals is the necessity to reduce barriers to participation in nuclear science. Our community is committed to establishing and maintaining an environment where all feel welcome and are treated with respect and dignity.

1.6 SYNERGIES WITH OTHER RESEARCH DISCIPLINES

In the quest to understand the origin and structure of the universe, nuclear science has emerged as a very broad field, connecting to other fields, such as atomic physics, condensed matter physics, high energy physics, astronomy, and cosmology. Many examples describing these powerful synergies have been articulated throughout this Long Range Plan. Since the last Long Range Plan, the historic detection of gravitational waves from the binary merger of two neutron stars (GW170817) has forged an exciting new partnership with the gravitational wave community. Indeed, whereas GW170817 has provided insights into the nature of dense matter and the synthesis of the heavy elements, nuclear physics provides the microscopic underpinning of the observed macroscopic phenomena.

1.7 INTERNATIONAL COORDINATION AND COLLABORATION

The field of nuclear physics is inherently international: a significant portion of users at the nation's accelerator facilities come from outside the United States. US-based experimenters lead programs at facilities abroad when those projects are complementary to the opportunities in the US; heavy ion research at the European Organization for Nuclear Research (CERN) LHC is a prime example. Across all subfields, international collaboration has led to major advances and propelled discovery, such as that of the new element tennessine in the periodic table. Concurrently, collaboration and cooperation in nuclear theory are not limited by borders and have always been international. In addition, NSAC maintains strong ties and collaboration with sister organizations in Europe (NuPECC) and Asia (ANPhA).

The search for neutrinoless double beta decay is a truly international effort, propelled by the compelling and fundamental discovery nature of the science. Three ton-scale projects (CUPID, LEGEND-1000, and nEXO) are all led by distinctly international collaborations with significant US leadership and responsibilities. International cooperation between funding agencies on double beta decay experiments is well organized and strong: two international summits have been held already, and a third is planned for early 2024. These stakeholders formed an International Working Group to coordinate efforts and to advance the field efficiently and cost-effectively.

The unique opportunities provided by the construction of the EIC facility in the United States have generated interest from scientists all over the world, reflected most clearly in the global composition of the ePIC collaboration: nearly 60% of the member institutions are based outside of the United States and are contributing significant resources and effort toward the detector design and construction. Similarly, the EIC Users Group, which includes ePIC collaborators as well as theoretical and accelerator physicists, represents a worldwide effort—the largest contributions come from North American (40%), European (30%) and Asian (25%) institutions. The EIC construction project reinforces US leadership in nuclear and accelerator science. At the same time, international interest and support (e.g., the Inter-American Network of Networks of QCD Challenges, funded by NSF) are critical to its success.

1.8 RESOURCES

Implementation of this Long Range Plan will yield important scientific discoveries and societal benefits, which can be accomplished through continued investment in the people who conduct nuclear science research and in the facilities and equipment they use to do so. The long-range planning process included careful consideration of the current and future DOE NP and NSF Directorate for Mathematical and Physical Sciences (MPS) budgets. Investments by the American taxpayer have given DOE NP an impressive suite of four national user facilities where world-leading experiments are performed. Operating these facilities at the optimal level is laudable. However, in the last few years, budgetary constraints have meant that optimal facility operation comes at the cost of other community priorities. The wealth of data coming from the national user facilities will not benefit the United States if insufficient funding is available for the nuclear science researchers who reveal the science by analyzing the data and by developing and refining nuclear physics models and theory. Recent mandates that facilities operate at optimal levels have resulted in an overall DOE NP funding profile that has seen the erosion of research support. One particularly stark consequence is that most present graduate stipends are inadequate to support basic necessities. Hence the community's primary recommendation is to increase funding to the research program to a level that will enable capitalizing on the optimal operation of DOE NP facilities.

Funding at the level of the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act, which was passed after the charge was issued to NSAC, would allow such an increase, enhancing the intellectual capital that drives innovation. It would also enable continued optimized operation of the national user and university-based facilities while funding projects critical to maintaining US leadership in nuclear science. These projects include experiments to study neutrinoless double beta decay and the construction of the EIC, which requires development of cutting-edge accelerator technology, on an aggressive, technically driven timescale.

A nuclear science budget consistent with modest growth over inflation would require deliberate choices while still permitting the nuclear physics community to deliver a compelling program of discovery science and benefits for the nation. In this scenario, the EIC can be realized with a two-year delay (relative to the CHIPS timeline), modest investments in the research community will address the most pressing issues, and neutrinoless double beta decay experiments can take place over a drawn-out period. Additionally, the national user facilities could run a program of exciting science, albeit with reduced impact owing to reduced operating funds, which may delay discoveries.

1.9 THE PAGES AHEAD

This Long Range Plan summarizes the significant progress since the 2015 Long Range Plan and presents exciting opportunities for the future that will ensure the United States remains at the forefront of nuclear science. Chapter 2 provides an overview of the nuclear science ecosystem and the impact of the field on society. Chapter 3 through Chapter 6 cover the science of four nuclear subfields: QCD, nuclear structure and nuclear reactions, nuclear astrophysics, and fundamental symmetries. Chapter 7 presents an overview of how nuclear theory spans and connects the subdisciplines with each other and with other fields. Chapter 8 addresses the many ideas our community has developed to address workforce needs for nuclear science and for the nation. Chapter 9 provides an overview of the suite of facilities and tools associated with experimental and computational nuclear science. Chapter 10 summarizes cross-cutting and interdisciplinary opportunities, and Chapter 11 summarizes applications of nuclear science. Chapter 12 describes the resources needed to realize the opportunities articulated in Chapters 3–11. We stand on the verge of a new era of discovery in nuclear science. The new discoveries, new tools, and new impact that we describe in these pages will ensure that the United States reaps the benefits of its ongoing investment in scientific discovery.

Appendix D

NSAC Facilities Subcommittee

Christine Aidala (Chair)	University of Michigan
Michael Carpenter	Argonne National Laboratory
Vincenzo Cirigliano	University of Washington
Gail Dodge	Old Dominion University
Renee Fatemi	University of Kentucky
Krishna Kumar	University of Massachusetts Amherst
Sherry Yennello	Texas A&M University
Xiaochao Zheng	University of Virginia

Appendix E

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January 12, 2024

Professor Christine Aidala
Department of Physics
University of Michigan
450 Church Street
Ann Arbor, Michigan 48109

Dear Professor Aidala,

As you know, Dr. Asmeret Asefaw Berhe, Director of the Office of Science at the Department of Energy, has requested that NSAC evaluate new facilities and projects over $100 million in terms of (a) potential to contribute to world leading science in the next decade, and (b) readiness for construction. The details are described in the attached charge. We have received the attached list of projects to consider from the DOE Office of Nuclear Physics. I am writing to formally ask you to serve as the Chair of this NSAC Subcommittee to consider this charge and to report back to NSAC. The assessment should be prepared and submitted to NSAC by early April. We will schedule an NSAC meeting to receive the report in April or May.

Your committee should be guided by the recently completed 2023 Long Range Plan for Nuclear Science, *A New Era of Discovery*. The subcommittee may add projects to the list in consultation with the Designated Federal Officer (Tim Hallman) and with me as NSAC Chair.

I realize this is a heavy responsibility and a burden on your time and that of the Subcommittee. I, and our whole community, will owe you an enormous debt of gratitude.

Sincerely yours,

Gail E Dodge

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Chair NSAC
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