## Nuclear Physics

### Overview

One of the enduring mysteries of the universe is the nature of matter—what are its basic constituents and how do they interact to form the properties we observe? The largest contribution by far to the mass of the visible matter we are familiar with comes from protons and heavier nuclei. The mission of the Nuclear Physics (NP) program is to discover, explore, and understand all forms of nuclear matter. Although the fundamental particles that compose nuclear matter—quarks and gluons—are themselves relatively well understood, exactly how they interact and combine to form the different types of matter observed in the universe today and during its evolution remains largely unknown. Nuclear physicists seek to understand not just the familiar forms of matter we see around us, but also exotic forms such as those that existed in the first moments after the Big Bang and that exist today inside neutron stars, and to understand why matter takes on the specific forms now observed in nature.

Nuclear physics addresses three broad, yet tightly interrelated, scientific thrusts: **Quantum Chromodynamics (QCD); Nuclei and Nuclear Astrophysics**; and **Fundamental Symmetries**:

- **QCD** seeks to develop a complete understanding of how the fundamental particles that compose nuclear matter, the quarks and gluons, assemble themselves into composite nuclear particles such as protons and neutrons; how nuclear forces arise between these composite particles that lead to nuclei; and how novel forms of bulk, strongly interacting matter behave, such as the quark-gluon plasma that formed in the early universe.
- **Nuclei and Nuclear Astrophysics** seeks to understand how protons and neutrons combine to form atomic nuclei, including some now being observed for the first time, and how these nuclei have arisen during the 13.8 billion years since the birth of the cosmos.
- **Fundamental Symmetries** seeks to develop a better understanding of fundamental particle interactions by studying the properties of neutrons and by performing targeted, single focus experiments using nuclei to study whether the neutrino is its own anti-particle. Neutrinos are very light, nearly undetectable fundamental particles produced during interactions involving the weak force, through which they were first indirectly observed in nuclear beta decay experiments.

The quest to understand the properties of different forms of nuclear matter requires long-term support for both theoretical and experimental research efforts within the NP portfolio. Theoretical approaches are based on calculations of the interactions of quarks and gluons described by the theory of QCD using today's most advanced computers. Quantum computing holds great potential for obtaining solutions to many-body QCD problems that are intractable with today's computers. Other theoretical research that models the forces between nucleons seeks to understand and predict the structure of nuclear matter. Most experimental approaches in nuclear physics use large accelerators that collide particles at nearly the speed of light, producing short-lived forms of matter for investigation. Nuclear physics also uses low-energy, precision nuclear experiments, many enabled by new quantum sensors to search for a deeper understanding of fundamental symmetries and nuclear interactions. Comparing experimental observations and theoretical predictions tests the limits of our understanding of nuclear matter and suggests new directions for experimental and theoretical research.

Highly trained scientists who conceive, plan, execute, and interpret transformative experiments are at the heart of the NP program. NP supports these university and national laboratory scientists, and U.S. participation in select international collaborations, resulting in an average of approximately 90 Ph.D. degrees awarded annually to students for research supported by the program. DOE NP is the steward of the nation's fundamental nuclear physics research portfolio; in FY 2019, DOE provided over 91 percent and the National Science Foundation (NSF) less than 9 percent of the total investment in the U.S. nuclear physics basic research portfolio. As documented in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP) for Nuclear Science, Reaching for the Horizon[a], over 40 percent of the scientists who receive Ph.D.'s in nuclear science find careers in sectors other than academia and DOE research laboratories, serving national needs in defense, computing, cutting-edge technology, government, and industry. DOE's mission and priorities guide NP research, which in turn develop the core competencies and expertise needed to achieve the goals of the NP

[a] "*Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science*." Nuclear Science Advisory Committee, October 2015 (https://science.osti.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf).

program and train the next generation of nuclear scientists. National laboratory scientists work and collaborate with academic scientists and other national laboratory experimental and theoretical researchers to acquire and analyze large volumes of data, and to construct, support, and maintain the advanced instrumentation and world-class accelerator facilities used in experiments. The national laboratories provide state-of-the-art resources for targeted detector and accelerator R&D for future upgrades and new facilities. This research develops knowledge, technologies, and trained scientists to design and build next-generation NP accelerator facilities, and is relevant to machines being developed by other domestic and international programs. The technologies developed to simulate, sense, collect, and analyze nuclear physics data have synergy with quantum information science (QIS), artificial intelligence (AI), machine learning (ML), microelectronics, isotope production science, and data integration.

The world-class scientific user facilities and associated instrumentation necessary to advance the U.S. nuclear science program are large and complex, and account for a significant portion of the NP budget. NP supports three scientific user facilities: the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL); the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (TJNAF); and the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL). Each of these facilities has unique capabilities that advance the scientific thrusts outlined in the 2015 LRP. In FY 2021, these facilities will provide particle beams for an international user community of almost 2,000 research scientists. Approximately 35 percent of these researchers are from institutions outside of the U.S., and they provide very significant benefits including leveraging the U.S. program through contributed capital, human capital, and experimental equipment, as well as intellectual contributions. Researchers supported by other SC programs such as High Energy Physics (HEP) and Basic Energy Sciences (BES); other DOE offices such as the National Nuclear Security Administration (NNSA) and Nuclear Energy (NE); other Federal agencies such as NSF, the National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD); and industries, use NP scientific user facilities and core competencies to carry out research programs important for their respective missions. Construction of the Facility for Rare Isotope Beams (FRIB), a world-class nuclear physics scientific user facility with unique capabilities in nuclear structure and astrophysics, is nearing completion at Michigan State University (MSU), according to the baseline cost and schedule. This project is over 92 percent complete and will provide exciting new capabilities in nuclear structure and astrophysics to better understand the landscape of the periodic table of elements. In FY 2021, FRIB will transition to operations as a DOE SC User Facility for nuclear physics.

The 2015 NSAC LRP for Nuclear Science recommended a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction. Consistent with that vision, in 2016 NP commissioned a National Academy of Sciences (NAS) study by an independent panel of external experts to assess the uniqueness and scientific merit of such a facility. The report[a], released in July 2018, strongly supports the scientific case for building a U.S.-based EIC, documenting that an EIC will advance the understanding of the origins of nucleon mass, the origin of the spin properties of nucleons, and the behavior of gluons. Subsequently, DOE determined that the construction of an EIC is the highest priority for new facility construction in the U.S. Nuclear Physics Program to maintain U.S. leadership in nuclear physics and accelerator science. The EIC will enable scientists to investigate and answer questions about the basic building blocks of nuclei and how quarks and gluons, the particles inside neutrons and protons, interact dynamically via the strong force to generate the fundamental properties of neutrons and protons, such as mass and spin.

The Secretary of Energy approved Critical Decision-0, Approve Mission Need*,* on December 19, 2019, with a rough order of magnitude cost range of $1.6 billion to $4.2 billion. An Independent Cost Review, conducted by the DOE Office of Project Management as is required for projects of this magnitude, determined the cost range for CD-0. DOE conducted an Independent Site Selection Assessment and selected BNL to host the EIC facility for the Nation. This selection establishes a cost range of $1.6 billion to $2.6 billion for the EIC. Both BNL and TJNAF will have essential and major roles in both the construction of the EIC and the realization of the facility's full scientific opportunities.

Involving students in the development and construction of NP facilities and advanced instrumentation, as well as accelerator technology and computational techniques, helps to develop the highly trained workforce needed in the field of nuclear science. In addition to significant advances in discovery science, these facilities and techniques provide collateral

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[a] National Academies of Sciences, Engineering, and Medicine. 2018. *An Assessment of U.S.-Based Electron-Ion Collider Science.* Washington, D.C.: The National Academies Press. https://doi.org/10.17226/25171

benefits such as the creation of new technologies with broad-based applications in industry and society, such as AI/ML , QIS, and computational and data infrastructure . NP supports cutting-edge accelerator R&D that is specific to the programmatic needs of its current and planned facilities. In the process, transformative technological advances and core competencies in accelerator science that are developed by NP are also often relevant to other applications and other SC programs. For example, superconducting radio frequency (SRF) particle acceleration developed for NP programmatic missions has provided technological advances for a broad range of applications including materials research, cancer therapy, food safety, bio-threat mitigation, national defense, waste treatment, and commercial fabrication. NP coordinates closely with other SC accelerator R&D activities to exploit synergies and avoid duplication of efforts.

**Highlights of the FY 2021 Request**

The FY 2021 Request for $653,327,000 supports the highest priority efforts and capabilities in nuclear science to optimize scientific productivity and impact on national priorities. World-class experimental user facilities and theoretical and experimental nuclear physics research will continue to enable advances in science. Core research groups will be re-organized and to target select scientific opportunities to promote U.S. competitiveness in nuclear physics. NP will prioritize increasing operations of scientific user facilities and participation in administration research priorities. Supported instrumentation, facilities and construction projects closely align to guidance from NAS studies and the NSAC LRP, and promote U.S. leadership in nuclear science. The Request will continue support for world-class discovery science research and R&D integration to facilitate the development of state-of-the-art applications for medicine, commerce, and national security. The Request continues support for the EIC at BNL, with partnership of TJNAF andother national labs essential to its success.

The Request places an emphasis on Administration research priorities, with increased participation of NP in coordinated SC initiatives, including QIS and AI/ML. The Request also prioritizes research to support the DOE Isotope Initiative, and NP participation in the Strategic Accelerator Technology Initiative. FY 2021 will be the first year of support for the Strategic Accelerator Technology Initiative and the first year of NP support for AI/ML. A community roundtable discussion in FY 2020 on the role of NP in AI/ML highlighted how the NP community could best incorporate AI/ML research, for example by using ML to facilitate effective accelerator operations. Initial funding for the Strategic Accelerator Technology Initiative will enable the pursuit of transformative accelerator R&D initiatives, including next generation electron ion source developments and advanced approaches in SRF technology. There are strong synergies between these different activities and the unique needs and core competencies of the nuclear physics community.

The Request also increases support for the DOE Isotope Program (DOE IP), a DOE priority, to introduce new medical isotopes to the community for clinical trials and cancer therapy, and create isotope harvesting capability at FRIB. The Request supports development of isotope processing core competencies and capabilities at universities and laboratories to increase isotope availability for a suite of applications, including industrial radiography, medical isotope production feedstock, and explosives detection. New stable isotope enrichment capabilities replenish U.S. inventory and reduce foreign dependence on isotopes of strategic importance for the Nation. The Request continues funding for the U.S. Stable Isotope Production and Research Center (U.S. SIPRC). U.S. SIPRC's objective is to mitigate U.S. dependence on foreign sources of enriched stable isotopes for research and applications. DOE continues its focus on an isotope initiative that will expand and develop core competencies and technology critical for long-term U.S. leadership and independence in isotope production.

The Request supports research activities in Nuclear Structure and Astrophysics described separately from the Fundamental Symmetries activities within the Low Energy Subprogram, in an effort to better articulate the breadth of the program and capture the growing effort in fundamental symmetries of nuclear physics. Limited fundamental symmetries research supported in the Medium Energy Subprogram, primarily those efforts associated with the Moller Experiment that will operate at TJNAF, are moved into the Fundamental Symmetries Subprogram to promote consistency between the scientific focus of the MOLLER experiment and the intellectual thrust of the Fundamental Symmetries portfolio.

<u>Research</u>

The Request for Research supports key university and laboratory researchers to nurture critical core competencies and enable the highest priority theoretical and experimental activities to target compelling scientific opportunities at the frontier of nuclear science, and in concert with guidance from the NAS and the NSAC. Research funding is also provided for QIS, AI/ML, transformative accelerator R&D, and isotope production R&D. The Request supports world-class research in all scientific thrusts of nuclear science including:

- Experimental and theoretical research aimed at unravelling the mechanism of quark confinement with the upgraded 12 gigaelectronvolt (GeV) CEBAF.
- Discovery research at RHIC, the nation's only remaining collider, to search for a critical point in the phase diagram of QCD matter and further characterize the quark-gluon plasma (QGP), a form of matter discovered at RHIC that last existed at the beginning of the cosmos.
- Targeted collaboration in the heavy ion program at the CERN Large Hadron Collider (LHC) to provide U.S. researchers the opportunity to investigate states of matter under substantially different initial conditions than those provided by RHIC, providing complementary information regarding the matter that existed during the infant universe.
- Challenging new experiments at ATLAS to study nuclear structure and nuclear reactions occurring under extreme conditions in the cosmos that are conjectured to play a central role in the synthesis of heavy elements.
- Pioneering R&D in the search for neutrino-less double beta decay, a process that if observed would prove that the neutrino is its own anti-particle is supported.
- Continuation of the High Rigidity Spectrometer (HRS) instrumentation for FRIB, which will enable the most sensitive experiments across the entire span of known nuclei, thereby enabling experiments with the most neutron-rich nuclei available at FRIB.
- Research delving into the nature of the neutron at the Fundamental Neutron Physics Beamline at the Spallation Neutron Source (SNS), and the continued development of the high-risk, high-discovery potential Neutron Electric Dipole Moment (nEDM) experiment, that could shed light on why there is more matter than anti-matter in the universe.
- Other Project Cost (OPC) activities including accelerator and detector R&D for the EIC.
- Continuation of funding for the SC QIS Center(s) that will be established in FY 2020 and which will be an interdisciplinary partnership among SC programs in support of the National Quantum Initiative. This partnership complements a robust core research portfolio stewarded by the individual SC programs to create the ecosystem across universities, national laboratories, and industry that is needed to advance developments in QIS and related technology. Innovative NP research in QIS enables precision nuclear physics measurements, quantum simulations with trapped ions, quantum computing solutions to otherwise intractable QCD challenges, development of quantum sensors based on atomic-nuclear interactions and quantum control (coherent control) techniques, and the production of stable isotopes for next generation QIS.
- Accelerator R&D , which is a core capability SC stewards for the Nation. Sustained investment is needed for the U.S. to continue to provide the world's most comprehensive and advanced accelerator-based facilities for scientific research, and to continue to attract and train the workforce needed to design and operate these facilities. NP will support high priority accelerator R&D of relevance to NP next-generation machines and optimal performance of existing machines.
- Targeted cutting-edge techniques based on AI/ML of relevance to nuclear science research, accelerator facility operations, and automated machine operations within the DOE IP.
- Forefront isotope R&D to develop new production methods for critical isotopes in high demand for the Nation, including isotopes for medicine that could revolutionize therapy for metastasized cancer, and the development of enriched stable isotope production capabilities to reduce dependence on foreign supplies and produce isotopes for quantum computing.
- Support for core competencies in developing and operating a broad array of isotope enrichment technologies, critical for research and applications, through research in support of the initiation of the DOE Isotope Initiative.

Facility Operations

The Request for Facility Operations includes funding for the operations of the NP scientific user facilities. Requested funding directs efforts to operations of the facilities to enable world-class science and the optimization of existing capabilities including:

- Support for RHIC to operate for 2,580 hours (100 percent optimal) in FY 2021. Operating hours are capped in FY 2021 due to planned installation requirements. Planned operations with the completed Low Energy RHIC e-Cooler (LEReC) will further increase luminosity to carry out a definitive search for a critical point in the phase diagram of QCD matter. Investments in accelerator improvement projects and capital equipment maintain robust operations and upgrades of the RHIC Access Control System continue.

- Support for CEBAF to operate for 3,010 hours (68 percent optimal) in FY 2021, enabling the highest priority experiments of the 12 GeV science program. Targeted investments in accelerator improvement projects and capital equipment modernize SRF equipment.
- Support for ATLAS to operate as the world's premiere stable ion beam facility for 2,980 hours (44 percent optimal) to enable the most compelling experiments in nuclear structure and astrophysics. Investments in high priority accelerator improvement projects and capital equipment focus on new scientific instrumentation and the Multi-User Upgrade.
- Operations funding for FRIB in FY 2021, which partially supports a transition from a construction project to operations of a scientific user facility, including the movement of key operational staff from the project to the facility operations budget.
- Support for the experimental physics University Centers of Excellence including the Center for Experimental Nuclear Physics and Applications (CENPA) at the University of Washington, the Research and Engineering Center at the Massachusetts Institute for Technology (MIT), the High Intensity Gamma Source (HIGS) at Duke University, and the Texas A&M Cyclotron Institute at the Texas A&M University . These centers provide niche capabilities and unique "hands-on" experiences in nuclear science.
- Funding to fully support mission readiness and nurture critical core competencies at the isotope production facilities. These facilities produce isotopes in short supply that are critical to the nation's federal complex, research enterprise and industry. University isotope production capabilities are increased and networked into the DOE IP for the production of high priority short-lived isotopes. Operation of the Enriched Stable Isotope Prototype Plant (ESIPP) increases to replenish U.S. inventory, reduce dependence on foreign suppliers for research quantities of stable isotopes, and produce isotopes for quantum systems. Investments are made to enhance processing capabilities to keep pace with the growing portfolio of radioisotopes, generate inventories of isotopes in short supply, increase helium-3 supply, continue the FRIB Isotope Harvesting accelerator project, develop electromagnetic separation capabilities for the enrichment of radio-isotopes and heavy stable isotopes, and extract valuable isotopes from the legacy Mark 18a targets, in coordination with NNSA.

<u>Projects</u>

The Request for Construction and Major Items of Equipment (MIEs) includes:

- The final year of construction funding for the Facility for Rare Isotope Beams (FRIB), which will provide world-leading capabilities for nuclear structure and nuclear astrophysics. The project continues to make impressive progress and is over 92 percent complete. Construction funding continues according to the baselined profile.
- Continuation of design efforts and Project Engineering Design (PED) activities for the EIC. The FY 2018 NAS confirmed the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. The Secretary of Energy approved CD-0, Approve Mission Need, in December 2019.
- Continuation of engineering design and long lead procurements for U.S. SIPRC to significantly increase the domestic production capabilities of stable isotopes for scientific, industrial, national security and medical uses. U.S. SIPRC will mitigate. U.S. dependency on foreign supply of stable isotopes.
- Continuation of the Gamma-Ray Energy Tracking Array (GRETA) MIE, which will enable provision of advanced, high resolution gamma ray detection capabilities for FRIB.
- Continuation of the super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) MIE, which will have enhanced capabilities that will further RHIC's scientific mission by studying high rate jet production. This project is implemented with funding from within the RHIC facility operations budget.
- Continuation of the Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) MIE, which will measure the parity-violating asymmetry in polarized electron-electron scattering with the 12 GeV CEBAF machine. This experiment will search for evidence of physics beyond our current understanding with unprecedented levels of precision, by comparing extremely small deviations in the outcomes of scattering experiments with the predictions of theory.
- Continuation of the international Ton-scale Neutrinoless Double Beta Decay MIE to determine whether the neutrino is its own antiparticle. CD-0, Approve Mission Need, was approved in FY 2019. Funding in FY 2021 supports high priority activities and the management team.

**FY 2021 Research Initiatives**

Nuclear Physics supports the following FY 2021 Research Initiatives.

| | (dollars in thousands) | | | |
|---|---|---|---|---|
| | **FY 2019 Enacted** | **FY 2020 Enacted** | **FY 2021 Request** | **FY 2021 Request vs FY 2020 Enacted** |
| **New Research Initiatives** | | | | |
| Strategic Accelerator Technology Initiative | — | — | 1,000 | +1,000 |
| **Total, New Research Initiatives** | **—** | **—** | **1,000** | **+1,000** |
| | | | | |
| **Ongoing Research Initiatives** | | | | |
| Artificial Intelligence and Machine Learning | — | — | 4,000 | +4,000 |
| DOE Isotope Initiative | — | 3,241 | 16,500 | +13,259 |
| Quantum Information Science | 8,300 | 10,300 | 13,000 | +2,700 |
| **Total, Ongoing Research Initiatives** | **8,300** | **13,541** | **34,500** | **+20,959** |

**Nuclear Physics**
**Funding**

| | (dollars in thousands) | | | |
|---|---|---|---|---|
| | **FY 2019 Enacted** | **FY 2020 Enacted** | **FY 2021 Request** | **FY 2021 Request vs FY 2020 Enacted** |
| **Medium Energy Nuclear Physics** | | | | |
| Research | 43,286 | 41,154 | 36,000 | -5,154 |
| Operations | 117,390 | 122,110 | 118,000 | -4,110 |
| Other Research | 3,553 | 3,600 | 2,800 | -800 |
| SBIR/STTR | 19,961 | 20,725 | 19,438 | -1,287 |
| **Total, Medium Energy Nuclear Physics** | **184,190** | **187,589** | **176,238** | **-11,351** |
| **Heavy Ion Nuclear Physics** | | | | |
| Research | 37,354 | 37,661 | 31,518 | -6,143 |
| Operations | 193,125 | 196,651 | 194,928 | -1,723 |
| Other Project Costs | — | 10,000 | 1,500 | -8,500 |
| **Total, Heavy Ion Nuclear Physics** | **230,479** | **244,312** | **227,946** | **-16,366** |
| **Low Energy Nuclear Physics** | | | | |
| Research | 70,530 | 70,998 | 60,336 | -10,662 |
| Operations | 30,215 | 55,739 | 50,241 | -5,498 |
| **Total, Low Energy Nuclear Physics** | **100,745** | **126,737** | **110,577** | **-16,160** |
| **Nuclear Theory** | | | | |
| Theory Research | 46,469 | 43,062 | 46,540 | +3,478 |
| Nuclear Data | 8,858 | 8,800 | 7,726 | -1,074 |
| **Total, Nuclear Theory** | **55,327** | **51,862** | **54,266** | **+2,404** |

| | (dollars in thousands) | | | |
|---|---|---|---|---|
| | **FY 2019 Enacted** | **FY 2020 Enacted** | **FY 2021 Request** | **FY 2021 Request vs FY 2020 Enacted** |
| **Isotope Development and Production for Research and Applications** | | | | |
| Research | 9,808 | 11,500 | 22,000 | +10,500 |
| Operations | 33,9451 | 35,900 | 44,000 | +8,100 |
| Other Project Costs | 500 | 2,100 | — | -2,100 |
| **Total, Isotope Development and Production for Research and Applications[a]** | **44,259** | **49,500** | **66,000** | **+16,500** |
| **Subtotal, Nuclear Physics** | **615,000** | **660,000** | **635,027** | **-24,973** |
| | | | | |
| **Construction** | | | | |
| 20-SC-51, U.S. Stable Isotope Production and Research Center | — | 12,000 | 12,000 | — |
| 20-SC-52, Electron Ion Collider | — | 1,000 | 1,000 | — |
| 14-SC-50, Facility for Rare Isotope Beams | 75,000 | 40,000 | 5,300 | -34,700 |
| **Total, Construction** | **75,000** | **53,000** | **18,300** | **-34,700** |
| **Total, Nuclear Physics** | **690,000** | **713,000** | **653,327** | **-59,673** |

SBIR/STTR funding:

- FY 2019 Enacted: SBIR $17,588,000 and STTR $2,373,000
- FY 2020 Enacted: SBIR $18,257,000 and STTR $2,468,000
- FY 2021 Request: SBIR $17,220,000 and STTR $2,218,000

[a] All appropriations for the Isotope Development and Production for Research and Applications subprogram fund a payment into the Isotope Production and Distribution Program Fund as required by P.L. 101–101 and as modified by P.L. 103–316.

## Nuclear Physics
## Explanation of Major Changes

| | (dollars in thousands) FY 2021 Request vs FY 2020 Enacted |
|---|---|
| **Medium Energy Nuclear Physics** | **-11,351** |

The Request provides support for the CEBAF accelerator complex, including mission readiness of the four experimental halls, mission readiness of the accelerator, all power and consumables of the site, computing capabilities for data collection and analysis, cryogenics plant, scientific researchers on site and at other laboratories and universities, on site accelerator scientists and technicians, and operation of the recently upgraded CEBAF accelerator to support 3,010 operating hours (68 percent optimal), to exploit the capabilities afforded by the 12 GeV CEBAF Upgrade to address the highest priority scientific opportunities. Funding supports high priority research in heavy ion nuclear physics at universities and national laboratories. The Request provides support for experimental activities that will utilize the newly upgraded experimental halls to implement the 12 GeV CEBAF physics program. The Request continues high priority investments in capital equipment and accelerator improvement projects for CEBAF to maintain viability of the facility, and continues targeted investments in maintenance activities and cryomodule refurbishment at CEBAF to improve the performance and reliability of the machine. Key 12 GeV researchers from national laboratories and universities will implement, commission, and operate high priority new experiments at CEBAF. Scientists will play a leading role in the development of scientific instrumentation and accelerator components for the EIC. The Request provides support to initiate investment in the Strategic Accelerator Technology initiative.

| | |
|---|---|
| **Heavy Ion Nuclear Physics** | **-16,366** |

The Request provides funding for the RHIC accelerator complex, including mission readiness and development of the experimental halls and instrumentation, mission readiness of the suite of accelerators, all power and consumables of the site, cryogenics plant, computing capabilities for data taking and analysis, scientific researchers on site and at other laboratories and universities, on-site accelerator scientists and technicians, operation of RHIC for a 2,580 hour run (at 100 percent of the capped FY 2021 maximum operations), high priority core competencies, and experimental activities to prepare scientific instrumentation and infrastructure for the scientific program. The Request continues high priority investments in capital equipment and accelerator improvement to maintain viability of the facility. Funding from RHIC operations is provided for the base-lined sPHENIX MIE, which will study high rate jets of particles at RHIC. Funding  supports the highest priorities in the NP program, including heavy ion nuclear physics at universities and national laboratories. The Request provides support to initiate the Strategic Accelerator Technology initiative. The Request continues OPC for the EIC, which will enable scientists to play a leading role in R&D and the development of scientific instrumentation and accelerator components for the EIC.

| | (dollars in thousands) |
|---|---|
| | **FY 2021 Request vs FY 2020 Enacted** |
| **Low Energy Nuclear Physics** | **-16,160** |

The Request provides support for operations of two low energy user facilities: the ATLAS facility, which operates for 2,980 hours (about 44 percent optimal), and FRIB operations and research. Funding will support the highest priorities in the NP Program including investments in capital equipment and accelerator improvement; these investments will maintain viability of the ATLAS facility and add multi-user capability to address the oversubscription of the facility. The Request sustains operations of the 88-Inch Cyclotron at the Lawrence Berkeley National Lab (LBNL) for a limited in-house nuclear science program and an electronics irradiation capability for DOD and NASA. Funding for core research groups supports the highest priorities in the NP program, including research nuclear structure and astrophysics at universities and national laboratories. Funding supports the ongoing GRETA MIE; implementation of this detector at FRIB will represent a major advance in gamma-ray tracking detector technology that will impact nuclear science as well as detection techniques in homeland security and medicine. Funding is continued for the compelling High Rigidity Spectrometer to exploit the fast beam capabilities at FRIB. Funding continues cost-effective operations of the three experimental University Centers of Excellence: the Texas A&M Cyclotron Facility, the HIGS at the Triangle Universities Nuclear Laboratory, and the CENPA at the University of Washington.

Targeted support continues for neutrinoless double beta decay research to determine whether the neutrino is its own antiparticle; funding is continued for a world-leading ton-scale experiment MIE to reach unprecedented sensitivities. Funding in Fundamental Symmetries also supports efforts such as the Fundamental Neutron Physics Beamline at the SNS and the continued development of its flagship experiment, the nEDM experiment, to study neutron properties and matter/anti-matter asymmetries in the universe. Funding is continued for the MOLLER MIE, which will measure the parity-violating asymmetry in polarized electron-electron scattering at CEBAF.

| | |
|---|---|
| **Nuclear Theory** | **+2,404** |

Funding for Nuclear Theory is targeted to high priority activities, including theory research efforts at laboratories and universities, the U.S. Nuclear Data Program, specialized Lattice Quantum Chromodynamics (LQCD) computing hardware at TJNAF, and participation in the Science Discovery through Advanced Computing (SciDAC) program. The Request increases investments in QIS and quantum computing (QC), including R&D on quantum sensors to enable precision NP measurements, development of quantum sensors based on atomic-nuclear interactions, and development of quantum computing algorithms applied to quantum mechanical systems and NP topical problems. The Request initiates support for NP-related activities in AI/ML of relevance to nuclear science research, accelerator facility operations and automated machine operations.

| | (dollars in thousands) FY 2021 Request vs FY 2020 Enacted |
|---|---|
| **Isotope Development and Production for Research and Applications** Operations funding increases to support mission readiness at the expanding suite of isotope production and processing sites to meet U.S. demand for isotopes in short supply. Increased funding supports the production and processing capability for Actinium-225 and other promising cancer therapeutic isotopes for clinical trials and applications. The Request increases support for the FRIB Isotope Harvesting project at MSU that will add isotope harvesting capabilities to FRIB. The Request provides additional funding to increase isotope availability and production capabilities, including Helium-3 for cryogenics, Lithium (Li)-7 for reactor operations, infrastructure investments to increase processing capabilities of radioisotopes, and the development of new enrichment capabilities for stable and radio-isotopes. ESIPP operates to produce research quantities of enriched stable isotopes; efforts to develop production capabilities for isotopes of interest to next generation quantum information systems continues. The Request increases university and laboratory research in new isotope production techniques, particularly the development of novel isotopes for cancer therapy. Research in support of the DOE Isotope Initiative will enhance core competencies in the development and operation of a broad array of isotope enrichment technologies, critical for research and applications. The Request supports university operations for a network of university accelerators and reactors for cost-effective, regional production of short-lived isotopes for research and medical applications; this includes the University of Washington cyclotron and University of Missouri Research Reactor. | **+16,500** |
| **Construction** Construction funding decreases according to the baselined profile for the Facility for Rare Isotope Beams. Engineering effort and long-lead procurements continue on the new U.S. SIPRC to expand the Nation's capabilities for enriched stable isotopes. The Request includes funding for the EIC to continue Project Engineering and Design. | **-34,700** |
| **Total, Nuclear Physics** | **-59,673** |

**Basic and Applied R&D Coordination**

The NP mission supports the pursuit of unique opportunities for R&D integration and coordination with other DOE Program Offices, Federal agencies, and non-Federal entities. For example, researchers from the High Energy Physics (HEP), NP, and Advanced Scientific Computing Research (ASCR) programs coordinate and leverage forefront computing resources and/or technical expertise through the SciDAC projects and Lattice QCD research to determine the properties of as-yet unobserved exotic particles predicted by the theory of QCD, advance progress towards a model of nuclear structure with predictive capability, and dramatically improve modeling of neutrino interactions during core collapse supernovae. The U.S. Nuclear Data Program provides evaluated cross-section and decay data relevant to a broad suite of Federal missions and topics such as reactor design (e.g., of interest to the NE and Fusion Energy Sciences (FES) programs), materials under extreme conditions (of interest to the BES and FES programs), and nuclear forensics (NNSA and the Federal Bureau of Investigations (FBI)). NP leads an Interagency working group including NNSA, Department of Homeland Security (DHS), NE, the DOE IP and other Federal Agencies to coordinate targeted experimental efforts on opportunistic measurements to address serious gaps and uncertainties in existing nuclear data archives. NP research develops technological advances relevant to the development of advanced fuel cycles for next generation nuclear reactors (NE); advanced cost-effective accelerator technology and particle detection techniques for medical diagnostics and treatment (National Institutes of Health (NIH)); and research in developing neutron, gamma, and particle beam sources with applications in cargo screening (NNSA, DHS, and the FBI).

R&D coordination and integration are hallmarks of the NP Isotope Development and Production for Research and Applications subprogram (DOE IP), which produces commercial and research isotopes in short supply that are critical for basic research and applications. It also supports research on the development of new or improved production and separation techniques for stable and radioactive isotopes. NP continues to align the Federal, industrial, and research stakeholders of the DOE IP and has strong communication between the various communities. To ascertain current and future demands of the research and applied communities, NP organizes working groups, workshops, symposia, and discussions with Federal agencies and community and industrial stakeholders on a continuous basis. It also works collaboratively with other DOE Offices (NNSA, Intelligence and Counterintelligence (IN), Environmental Management (EM), and NE) to help ensure adequate supplies of isotopes needed for their missions, such as Li-7, which is used by nuclear power plants as a coolant reagent. The DOE IP conducts biennial Federal workshops to identify isotope demand and supply across a broad range of Federal agencies (including NIH, NASA, FBI, DOD, DHS, Department of Transportation, NSF, the National Institute of Standards and Technology, Office of the Director of National Intelligence, Department of State, and other DOE offices) to ensure that isotopes are available for the federal complex to accomplish its missions.

**Program Accomplishments**

*First beam from the world's highest energy continuous-wave hadron linear accelerator*

In March 2019, FRIB became the world's highest energy continuous-wave (non-pulsed beam)hadron linear accelerator following the successful demonstration of an accelerated beam of Argon ions up to 20.3 million electron-volts per nucleon (MeV/u) with 100 percent transmission and no detectable beam losses. The use of superconducting technology enables FRIB operation in continuous-wave mode in contrast to normal conducting accelerating structures that operate in pulsed-beam mode. FRIB has 100 superconducting radiofrequency cavities capable of a total accelerating voltage of 166 megavolts (MV) for any ion species. Existing heavy-ion superconducting linear accelerators are only capable of providing 100 MV total voltage for acceleration of hadron beams in continuous-wave mode. FRIB construction will be completed in 2022, at which point the number of isotopes available for nuclear structure and nuclear astrophysics research will more than double, including neutron –rich isotopes of great interest for understanding the synthesis of heavy elements (e.g. gold, platinum, etc.) in the cosmos.

*New evidence of a 'super-allowed' alpha-decay*

For the first time, researchers at the ATLAS facility located at ANL observed alpha (helium nucleus) emission in a relatively heavy 'self-conjugate' nucleus. Self-conjugate nuclei have the same number of protons and neutrons. They are particularly interesting since their characteristics can yield important insights for understanding nuclear structure and advancing theoretical models. Theoretical predictions suggest that self-conjugate nuclei might pre-form alpha particles inside them prior to their radioactive decay. The rate of alpha emission observed would then be faster than normal, appearing to evidence a so-called 'super-allowed' decay. New results searching for super-allowed decay rates on a number of nuclei that decay via alpha emission suggest, for example, that $^{108}$Xenon (Xe) and $^{104}$Tellurium (Te) may be thought of as a $^{100}$Tin (Sn) core nucleus coupled to one or two alpha particles, which are kept inside the nucleus by electromagnetic effects. This picture is a dramatic departure from previous models advancing understanding of how pre-formed clusters can exist in the structure of heavy nuclei.

*Groundbreaking Advances in Accelerator Technology*
Since its initial commissioning, RHIC has consistently exceeded performance expectations and provided scientific discoveries and technological advances unattainable at any other facility in the world. Research at RHIC often requires high rates of collisions between heavy nuclei fully stripped of their electron cloud, known as heavy ions. Achieving a high luminosity (rate of collisions) can be challenging due to the tendency of the heavy ion bunches in the beams to "blow up" or expand through intra-beam scattering. A "first ever" achievement recently accomplished at RHIC was the successful demonstration of bunched-beam electron cooling. The project, known as LEReC for Low-Energy RHIC electron Cooling, successfully demonstrated that "bunched" beams of electrons could be successfully matched using radio frequency (RF) technology to bunched beams of ions in the RHIC collider, allowing the electrons to dissipate unwanted motion of the ions, "cooling" the ion bunches in order to prevent their physical expansion with a corresponding loss in luminosity. The successful demonstration of bunched-beam electron cooling is a crucial advance necessary to enable the high-quality hadron beams required by future accelerators, including the planned EIC.

*Fifty-year-old enigma solved*
Beta decay, the process by which a nucleus converts one of its neutrons into a proton, accompanied by the emission of an electron, is largely responsible for synthesizing the heaviest elements in the cosmos during cataclysmic events like neutron star mergers. The details of this process are predictable in nuclear theory, so deviations from this behavior can provide an essential tool in searches for new physics beyond our present understanding. For over 50 years however, use of a phenomenological factor has been necessary to bring theoretical beta-decay calculations into agreement with experimental observations. Recently, state-of-the-art computations of beta decay in light and medium mass nuclei, as well as in the heavy nucleus $^{100}Sn$ were carried out by nuclear theorists at Oak Ridge National Laboratory (ORNL) and their international collaborators. These calculations, enabled in part by leadership class computing capabilities, included the effects of strong correlations in the nucleus and the coupling felt by two-nucleon pairs due to the weak force of nature, as well as the coupling of the weak force to two nucleons. The resulting calculations showed excellent agreement between theory and experiment, with no need for a phenomenological factor. This groundbreaking advance will be particularly important in future searches for neutrino-less double beta decay to determine whether the neutrino is its own anti-particle.

*Jets at the planned Electron-Ion Collider*
As evidenced at RHIC, high energy jets, appearing as collimated sprays of particles, are powerful tools for exploring the properties of the hot, dense matter created in head-on collisions of nuclei traveling nearly the speed of light. Theoretical nuclear physicists at Lawrence Berkeley National Laboratory recently demonstrated that jets can also be used to study the properties of "cold" nuclear matter under less extreme conditions. Specifically, sensitive "signatures" were developed to guide future experimental research by developing challenging jet reconstruction algorithms for use at the planned EIC, a next-generation, high-energy, high-luminosity particle accelerator with polarized beams for exploring the structure of nucleons and nuclei in unprecedented detail. The proposed measurements, electron-jet correlation studies, will play a central role in uncovering how the "macroscopic" properties of the proton (e.g. mass, spin) are dynamically generated by interactions of the quarks and gluons it contains.

*Availability of a heavy element named for the father of nuclear physics enables scientific advance*
For the first time in over sixteen years, Fermium was produced in the U.S. Fermium, named after Enrico Fermi who built the first nuclear reactor, is a heavy element in the periodic table. It is extraordinarily challenging to make in significant quantities, and can only be made in the U.S. in the High Flux Isotope Reactor (HFIR) at ORNL. In FY 2019, the DOE IP produced Fermium for the first time since 2003, enabling compelling heavy element chemistry research supported by BES. Fermium is of keen interest in heavy element chemistry research because it has a sufficiently massive nucleus that causes its electrons to behave in ways that depart from well-tested atomic theory. The research attributes this anomalous behavior to the possibility that for such heavy nuclei, the inner atomic electrons must travel so close to the speed of light that relativistic effects become significant. Fermium is now the heaviest element ever studied in the effort to further develop this aspect of atomic theory which promises groundbreaking new insights.

*Proton Radius Puzzle*

The charge radius of the proton, one of the most important building blocks of nature, is an urgent, unanswered puzzle of modern physics. By precisely measuring the energy levels of electrons orbiting a proton, its charge radius can be measured to an accuracy of about one percent. However, a new measurement in which a muon orbits the proton instead of an electron found the proton charge radius to be about four percent smaller. The discrepancy has led to speculation that the different between the two measurements might be due to physics beyond our present understanding. Recently, a precision experiment designed to measure the proton charge radius (the Proton Radius [PRaD] experiment) by a completely different technique was completed at TJNAF. PRaD scatters electrons off of protons contained in hydrogen gas, and improves upon previous electron-proton scattering experiments by catching electrons that scatter away at very small forward angles. This helps to accurately determine the protons' size by probing the outermost edges of its charge distribution. New results from PRaD bolster the case that the proton charge radius is smaller than previously thought, consistent with the measurements made using muons.

*Routine production achieved for actinium (Ac)-225 to support clinical trials of targeted alpha therapy*

A tri-lab effort with scientists from LANL, BNL and ORNL are routinely producing 100 milliCuries (mCi) batches of Ac-225 in a reliable and reproducible way. This milestone enabled the DOE IP to enter the market for Ac-225 and support a suite of clinical trials and medical research focused on targeted alpha therapy for metastasized cancers. In the past, targeted cancer therapy research using the promising alpha emitter Ac-225 had been limited by its availability. Leveraging the capabilities of LANL, BNL and ORNL, a new production route for Ac-225 was developed, utilizing the proton beams available at LANL and BNL and the processing capabilities at ORNL. The DOE IP is now scaling up production capability to be able to meet the needs of the growing number of clinical trials and patient treatment.

**Nuclear Physics**
**Medium Energy Nuclear Physics**

**Description**
The Medium Energy Nuclear Physics subprogram focuses primarily on experimental tests of the theory of the strong interaction, known as Quantum Chromodynamics (QCD). According to QCD, all observed nuclear particles, collectively known as hadrons, arise from the strong interaction of quarks, antiquarks, and gluons. The protons and neutrons inside nuclei are the best known examples of hadrons. QCD, although difficult to solve computationally, predicts what hadrons exist in nature, and how they interact and decay. Specific questions addressed within this subprogram include:

- What is the internal landscape of the protons and neutrons (collectively known as nucleons)?
- What does QCD predict for the properties of strongly interacting matter?
- What is the role of gluons and gluon self-interactions in nucleons and nuclei?

Various experimental approaches are used to determine the distribution of up, down, and strange quarks, their antiquarks, and gluons within protons and neutrons, as well as clarifying the role of gluons in confining the quarks and antiquarks within hadrons. Experiments that scatter electrons off of protons, neutrons and nuclei are used to clarify the effects of the quark and gluon spins within nucleons, and the effect of the nuclear medium on the quarks and gluons. The subprogram also supports experimental searches for higher-mass “excited states” and exotic hadrons predicted by QCD, as well as studies of their various production mechanisms and decay properties.

The Medium Energy Nuclear Physics subprogram supports research at and operation of the subprogram’s primary research facility, CEBAF at TJNAF, as well as the spin physics research that is carried out using RHIC at BNL. The subprogram provides support for spin physics research at RHIC, which is the only collider in the world that can provide polarized proton beams.

CEBAF provides high quality beams of polarized electrons that allow scientists to extract information on the quark and gluon structure of protons and neutrons from measurements of how the electrons scatter when they collide with nuclei. CEBAF also uses highly polarized electrons to make very challenging precision measurements to search for processes that violate a fundamental symmetry of nature, called parity, in order to search for physics beyond what is currently described by the Standard Model of particle physics. These capabilities are unique in the world. The increase in beam energy provided by the 12 GeV CEBAF Upgrade continues to open up exciting new scientific opportunities and secures continued U.S. world leadership in this area of physics. The upgrade construction project was successfully completed on cost and schedule in 2017, and the highly anticipated science program was launched in FY 2018. Some of the science goals of the 12 GeV experimental program include the search for exotic new quark anti-quark particles to advance our understanding of the strong force, evidence of new physics from sensitive searches for violations of nature’s fundamental symmetries, and a microscopic understanding in the 12 GeV energy regime of the internal structure of the proton, including origin of its spin, and how this structure is modified when the proton is inside a nucleus. Next generation instrumentation to fully exploit the capabilities of the 12 GeV CEBAF are implemented in FY 2021. Research at RHIC using colliding beams of spin-polarized protons, a capability unique to RHIC, is providing information on the spin of the proton in a kinematic range complementary to that at CEBAF to extend present knowledge beyond the kinematic boundaries accessible at CEBAF alone. Research support for CEBAF and RHIC includes laboratory and university scientific and technical staff needed to conduct high priority data analysis to extract scientific results. Complementary special focus experiments that require different capabilities can be conducted at the High Intensity Gamma-Ray Source (HIGS) at the Triangle Universities Nuclear Laboratory (TUNL) – an NP University Center of Excellence, FNAL, European laboratories, and elsewhere. The Research and Engineering Center of the Massachusetts Institute of Technology has specialized infrastructure used to develop and fabricate advanced instrumentation and accelerator equipment for the nuclear physics community.

A high scientific priority for this community is understanding how the fundamental properties of the proton such as its mass and spin are dynamically generated by the extraordinarily strong color fields resulting from dense systems of gluons in nucleons and nuclei. The answer to this question is key to addressing an outstanding grand challenge problem of modern physics: how QCD, the theory of the strong force, which explains all strongly interacting matter in terms of points-like quarks interacting via the exchange of gluons, acts in detail to generate the “macroscopic” properties of protons and neutrons. The planned facility to address this science is the EIC, to be located at BNL; the DOE approved CD-0, Approve

Mission Need, in December 2019. Scientists and accelerator physicists from the Medium Energy sub-program are strongly engaged and play significant leadership roles in the development of the scientific agenda and implementation of the EIC.

Transformative accelerator R&D efforts are pursued within the Strategic Accelerator Technology Initiative, including next generation electron ion source developments and advanced approaches in SRF technology. Accelerator scientist also pursue accelerator science aimed at improving the operations of existing facilities and developing next-generation facilities for nuclear physics.

The SBIR/STTR category provides funding in accordance with the Small Business Innovation Development Act and related legislation, resulting in commercialization opportunities in medicine, homeland security, defense, and industry, as well as products and services that benefit NP. The "Other" category includes funding to meet other obligations, such as the annual Lawrence Awards and Fermi Awards.

Research

The subprogram supports targeted, high priority research at universities, TJNAF, BNL, ANL, the Los Alamos National Laboratory (LANL), and LBNL and carries out high priority experiments at CEBAF, RHIC, and elsewhere. Scientists conduct targeted research to advance knowledge and to identify and develop the science opportunities and goals for next generation instrumentation and facilities, primarily for CEBAF and the EIC. Scientists participate in the development and implementation of targeted advanced instrumentation, including state-of-the-art detectors for experiments that may also have application in areas such as medical imaging instrumentation and homeland security. TJNAF staff focus on the 12 GeV experimental program, including implementation of select experiments, acquisition of data, and data analysis at select CEBAF experimental halls (Halls A, B, C, and D). Staff also participate in the RHIC spin program, and play critical roles in instrumentation development for the EIC. Researchers participate in the conceptual design of the EIC and development of scientific and experimental plans for the proposed machine. The subprogram also supports a visiting scientist program at TJNAF and bridge positions with regional universities as a cost-effective approach to augmenting scientific expertise at the laboratory and boosting research experience opportunities.

ANL scientists play a leadership role in new experiments in the 12 GeV scientific program, and are engaged in commissioning experiments, instrumentation development, and data taking. ANL scientists are engaged in planning for the construction of the EIC and its scientific instrumentation. Scientists continue precise measurements of the electric dipole moments of laser-trapped atoms as part of an intensive world-wide effort to set limits on QCD parameters and contribute to the search for possible explanations of the excess of matter over antimatter in the universe. Research groups at BNL and LBNL play leading roles in RHIC data analysis critical for determining the spin structure of the proton. Researchers at TJNAF are developing high current, polarized electron sources for next generation NP facilities.

Accelerator R&D research proposals for accelerator R&D from universities and laboratories specific to improving operations of current NP facilities or developing new NP facilities are evaluated by peer review through a single competition for funding that is included under the Heavy Ion and Medium Energy subprograms. FY 2021 is the first year of funding for the Strategic Accelerator Technology Initiative, which builds on the unique core competencies of NP accelerator scientists to develop transformative technology for the Nation, including next-generation accelerator ion sources, innovative and cost effective cryogenic systems, high gradient SRF cavities, and advancements in hadron beam cooling.

Operations

The subprogram provides Accelerator Operations funding for a team of accelerator physicists at TJNAF that operate CEBAF, as well as for power costs of operations and maintenance of the 12 GeV CEBAF. The Request supports high priority accelerator improvements aimed at addressing CEBAF reliability, and high priority capital equipment for research and facility instrumentation. Activities to increase the reliability and energy gradient of the machine remain a priority. Targeted efforts in developing advances in SRF technology relevant to improving operations of the existing machine continue. The core competency in SRF technology plays a crucial role in many DOE projects and facilities outside of nuclear physics (such as the BES Linac Coherent Light Source (LCLS II) project), and has broad applications in medicine and homeland security. For example, SRF R&D at TJNAF has led to improved land-mine detection techniques and carbon nanotube and nano-structure manufacturing techniques for constructing super-lightweight composites such as aircraft fuselages. TJNAF also has a core competency in cryogenics and has developed award-winning techniques that have led to more cost-effective operations at

TJNAF and several other SC facilities; their cryogenics expertise is being applied to the FRIB project and LCLS-II. TJNAF accelerator physicists help train the next generation of accelerator physicists, enabled in part by a close partnership with nearby universities and other institutions with accelerator physics expertise. Accelerator scientists play critical roles in the design development of the EIC. The subprogram provides Experimental Support for scientific and technical staff, as well as for critical materials and supplies needed for the implementation, integration, assembly, and operation of the large and complex CEBAF experiments. Simultaneous continuous wave (cw) polarized beam delivery to four experimental halls is one of the world-wide unique features of the CEBAF accelerator.

## Activities and Explanation of Changes

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| **Medium Energy Nuclear Physics** | **$187,589** | **176,238** | **-$11,351** |
| Research | $41,154 | $36,000 | -$5,154 |
| Funding supports key scientists participating in the highest priority experiments at the four experimental halls with 12 GeV CEBAF. This includes support for critical scientific workforce resident at TJNAF and outside universities and national laboratories that plan the scientific program; develop, implement and maintain scientific instrumentation; participate in the experimental runs to acquire data; analyze data and publish experimental results; and train students in nuclear science. Funding also continues targeted analysis of RHIC polarized proton beam data to learn more about the origin of the proton's spin and focused support for high priority accelerator R&D, as well as funding for the development of scientific instrumentation and plans for the EIC. | | The Request will support scientists, resident at TJNAF, RHIC, and outside universities and national laboratories, for participation in high priority experiments to acquire data; develop, implement, and maintain scientific instrumentation; analyze data and publish experimental results; and train students in nuclear science. The Request will continue targeted analysis of RHIC polarized proton beam data to learn more about the origin of the proton's spin. The Request will support the development of concepts for detectors to be used at the EIC and further develop the scientific program. The Request will also enable researchers to pursue accelerator science pertinent to improving current operations of NP facilities including applications of artificial intelligence, and it will provide initial support for the Strategic Accelerator Technology Initiative. | Funding will support core scientific workforce at universities and national laboratories conducting research related to CEBAF, RHIC, EIC and other facilities. The Request funding will initiate the Strategic Accelerator Technology Initiative. |

(dollars in thousands)

| FY 2020 Enacted | FY 2021 Request | Explanation of Changes<br>FY 2021 Request vs FY 2020 Enacted |
|---|---|---|
| Operations $122,110 | $118,000 | -$4,110 |
| Funding for operations of the newly upgraded CEBAF facility supports the continuation of high priority experiments in the 12 GeV science program. Funding supports 2,560 operational hours for research, tuning, and beam studies. The number of hours is limited by installation of cryoplant infrastructure. Funding also provides support for CEBAF operations, including mission readiness of the accelerator, all power and consumables of the site, cryogenics plant, high priority facility and instrumentation capital equipment, high priority accelerator improvement projects, and the key computing capabilities for data taking and analysis. Support is provided to maintain critical core competencies and essential accelerator scientists, engineers, and technicians, and RHIC operations staff. The End Station Refrigerator GPP project is fully funded. Funding supports accelerator R&D. | The Request for operations of the newly upgraded CEBAF facility will support the continuation of the high priority experiments in the 12 GeV science program. Funding will provide 3,010 operational hours for research, tuning, and beam studies. The Request supports CEBAF operations, including mission readiness of the accelerator, all power and consumables of the site, cryogenics plant, activities to reduce Helium consumption, high priority facility and instrumentation capital equipment, high priority accelerator improvement and GPP projects, and the key computing capabilities for data taking and analysis. The Request also will support maintenance of critical core competencies and accelerator scientists, engineers, and technicians, and operations staff. The Request will support targeted facility capital equipment and accelerator improvements to modernize SRF equipment. Lab GPP investments will advance the most urgent components of the Campus Strategy for infrastructure. The Request will also support the participation of accelerator scientists in accelerator R&D activities, including those for the EIC. | Funding will support increased CEBAF run time by 450 hours to approximately 68 percent of optimal operations. Within the overall funding level, GPP funding will decrease as the End Station Refrigerator project was fully funded in FY 2020. |
| Other Research $3,600 | $2,800 | -$800 |
| Funding provides for DOE and SC requirements. | The Request will meet DOE and SC requirements. | Funding will meet DOE and Office of Science central IT and working capital requirements. |
| SBIR/STTR $20,725 | $19,438 | -$1,287 |
| In FY 2020, SBIR/STTR funding is 3.65 percent of non-capital funding. | In FY 2021, SBIR/STTR funding will be at 3.65 percent of non-capital funding. | The SBIR/STTR funding will be consistent with the NP total budget. |

**Nuclear Physics**
**Heavy Ion Nuclear Physics**

## Description

The Heavy Ion Nuclear Physics subprogram focuses on studies of nuclear matter at extremely high densities and temperatures, directed primarily at answering overarching questions in Nuclear Physics, including:

- What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
- What governs the transition of quarks and gluons into pions and nucleons?
- What determines the key features of QCD and their relation to the nature of gravity and space-time?

At the Relativistic Heavy Ion Collider (RHIC) facility, scientists continue to pioneer the study of condensed quark-gluon matter at the extreme temperatures characteristic of the infant universe. The goal is to explore and understand unique manifestations of QCD in this many-body environment and their influence on the universe's evolution. In the aftermath of collisions at RHIC and at the Large Hadron Collider (LHC) at CERN, researchers have seen signs of the same quark-gluon plasma that is believed to have existed shortly after the Big Bang. With careful measurements, scientists are accumulating data that offer insights into the processes early in the creation of the universe, and how protons, neutrons, and other bits of normal matter developed from that plasma. Important avenues of investigation are directed at learning more about the physical characteristics of the quark-gluon plasma including exploring the energy loss mechanism for quarks and gluons traversing the plasma, determining the speed of sound in the plasma, establishing the threshold conditions (minimum nucleus mass and energy) under which the plasma can be formed, and discovering whether a critical point exists where there is a phase transition between normal nuclear matter and the quark-gluon plasma.

The RHIC facility places heavy ion research at the frontier of discovery in nuclear physics. RHIC is uniquely flexible, providing a full range of colliding nuclei at variable energies spanning the transition to the quark gluon plasma discovered at RHIC. The facility continues to set new records in performance for both integrated Au-Au luminosity at full energy and a number of other beam settings. This flexibility and performance enable a groundbreaking science program to answer outstanding questions about this exotic and fundamental form of matter and whether a critical point exists in the phase diagram of nuclear matter. Scientists participate in instrumentation upgrades, such as enhancements to the capabilities of the Solenoid Tracker at RHIC (STAR) detector, and an upgrade of the PHENIX detector to sPHENIX with funds previously used to operate the PHENIX detector. Accelerator physicists conduct accelerator R&D at RHIC in critical areas that include various types of cooling of high-energy hadron beams, high intensity polarized electron sources, and high-energy, high-current energy recovery linear accelerators. The RHIC facility is typically used by about 1,000 DOE, NSF, and foreign agency-supported researchers annually.

A compelling, persistent, high scientific priority for the U.S. nuclear science community has been understanding how the fundamental properties of the proton such as its mass and spin are dynamically generated by the extraordinarily strong color fields resulting from dense systems of gluons in nucleons and nuclei. The answer to this question is key to addressing an outstanding grand challenge problem of modern physics: how Quantum Chromodynamics, the theory of the strong force, which explains all strongly interacting matter in terms of points-like quarks interacting via the exchange of gluons, acts in detail to generate the "macroscopic" properties of protons and neutrons. In 2018, a National Academies study gave a strong endorsement to a U.S.-based EIC, and recognized its critical role in maintaining U.S. leadership in nuclear science and accelerator R&D[a]. In December 2019, DOE approved CD-0, Approve Mission Need, for the EIC with a Rough Order of Magnitude TPC range of $1.6 billion to $4.2 billion. In January 2020, BNL was selected as the location for the EIC resulting in a revised cost range of $1.6 billion to $2.6 billion. Scientists and accelerator physicists from the Medium Energy sub-program are strongly engaged and will play significant leadership roles in the development of the scientific agenda and implementation of the EIC.

The SC Strategic Accelerator Technology initiative leverages accelerator science core competencies within the NP program and supports transformative technology needed for the next generation of SC facilities. Core competencies exist at NP

[a] Report: https://www.nap.edu/read/25171/chapter/1

facilities in the areas of beam and collider physics, hadron beam cooling, high field superconducting magnets, superconducting radio frequency (SRF) technologies, ion source technologies, and AI/ML applications in operation of user facilities. This support is essential for maintaining strategic accelerator technology core competencies at SC-supported laboratories. Accelerator scientists also pursue accelerator science aimed at improving the operations of existing facilities and developing next-generation facilities for nuclear physics.

Collaboration in the heavy ion program at the LHC at CERN provides U.S. researchers the opportunity to investigate states of matter under substantially different initial conditions than those provided by RHIC, providing complementary information regarding the matter that existed during the infancy of the universe. Data collected by the ALICE, CMS, and ATLAS detectors confirm that the quark-gluon plasma discovered at RHIC is also seen at the higher energy, and comparisons of results from LHC to those from RHIC have led to important new insights. U.S. researchers have been making important scientific contributions to the emerging results from all three LHC experiments. In ALICE and CMS, U.S. researchers have been participating in developing and upgrading instrumentation for future heavy ion campaigns at the LHC.

<u>Research</u>
This activity supports targeted, high priority research at universities and at BNL, LBNL, LANL, and ORNLORNL to participate in essential efforts at RHIC and the LHC. U.S. commitments to the LHC "common funds", which are fees based on the level of U.S. scientist participation in the LHC program and the use of LHC computing capabilities, are deferred to FY 2022.

Supported university and national laboratory research groups employ personnel and graduate students for taking data within the RHIC heavy ion program; analyzing data; publishing results; conducting R&D of next-generation detectors; developing and implementing scientific equipment; and planning for future experiments. BNL, LBNL, and ORNL provide computing infrastructure for petabyte-scale data analysis and state-of-the-art facilities for detector and instrument development. Researchers participate in the conceptual design of the EIC and its scientific instrumentation, and development of experimental plans for the proposed facility.

Research proposals for accelerator R&D from universities and laboratories specific to improving operations of current NP facilities or developing new NP facilities are evaluated by peer review through a single competition for funding that is included under the Heavy Ion and Medium Energy subprograms. FY 2021 will be the first year of funding for the Strategic Accelerator Technology Initiative, which will exploit the unique core competencies of NP accelerator scientists to develop transformative technology for the nation, including next-generation accelerator ion sources, innovative and cost-effective cryogenic systems, high gradient SRF cavities, and advancements in hadron beam cooling.

<u>Operations</u>
The Heavy Ion activity supports the operations and power costs of the RHIC accelerator complex at BNL, which includes the Electron Beam Ion Source (EBIS), Booster, and the Alternating Gradient Synchrotron (AGS) accelerators that together serve as the injector for RHIC. Staff provides key experimental support to the facility, including the development, implementation, and commissioning of scientific equipment associated with the RHIC program. The FY 2021 Request supports high priority capital equipment and accelerator improvement projects at RHIC to promote enhanced and robust operations. In FY 2021, the only detector operating at RHIC will be STAR; PHENIX operations funding is redirected to continue the sPHENIX MIE. sPHENIX will enable scientists to study how the near-perfect Quark Gluon Plasma liquid, which has the lowest shear viscosity ever observed, arises from the strongly interacting quarks and gluons from which it is formed. The Low Energy RHIC electron Cooling (LEReC) Accelerator Improvement Project was commissioned in FY 2019 and has demonstrated cooling of low energy heavy ion beams with bunched electron beam; this achievement is projected to increase the RHIC luminosity by up to another factor of ten at the lowest beam energies.

RHIC operations have led to advances in accelerator physics which have, in turn improved RHIC performance and NP capabilities. These core competencies provide collateral benefits to applications in industry, medicine, homeland security, and other scientific areas outside of NP. RHIC accelerator physicists are providing leadership and expertise to reduce technical risk of relevance to a possible next-generation collider, including beam cooling techniques and energy recovery linacs. Accelerator physicists also play an important role in the training of next generation accelerator physicists, through support of graduate students and post-doctoral associates.

RHIC operations allow for parallel and cost-effective operations of the Brookhaven Linac Isotope Producer Facility (BLIP), supported by the DOE Isotope Program for the production of research and commercial isotopes critically needed by the Nation, and of the NASA Space Radiation Laboratory Program for the study of space radiation effects applicable to human space flight as well as electronics. Support for the mission readiness of BLIP is included in the Isotope subprogram, while collected revenues from customers support the production costs of the isotopes.

Other Project Costs

Scientists and accelerator physicists from both the Medium Energy and Heavy Ion subprograms are actively engaged in the development of the conceptual design of the EIC and its scientific instrumentation for the proposed facility. Activities advance the conduct of an alternative analysis and preparations for CD-1 approval. Consideration to integration of laboratory core competencies and participation from across the national laboratory complex and universities continues. Accelerator and detector R&D focus on reduction of remaining technical risks and value engineering.

## Nuclear Physics
## Heavy Ion Nuclear Physics

### Activities and Explanation of Changes

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| **Heavy Ion Nuclear Physics** | **$244,312** | **$227,946** | **-$16,366** |
| Research | $37,661 | $31,518 | -$6,143 |
| Researchers participate in high priority analysis and collection of data from RHIC to explore new phenomena in quark-gluon plasma formation. Funding provides targeted support for scientific workforce resident at RHIC and outside universities and national laboratories to develop, fabricate, implement and maintain scientific instrumentation; participate in select experimental runs to acquire data; analyze data and publish experimental results; develop scientific plans and instrumentation for the proposed EIC; and train students in nuclear science. Funding supports scientists to implement the sPHENIX MIE for the study of high rate particle jets. U.S. scientists participate in the highest priority heavy ion efforts at the international ALICE, CMS, and ATLAS LHC experiments. In addition, funding supports high priority accelerator R&D relevant to NP programmatic needs and EIC Conceptual Design. | | The Request will support scientists resident at RHIC and outside universities and national laboratories to develop, fabricate, implement and maintain scientific instrumentation; participate in select experimental runs to acquire data; analyze data and publish experimental results; develop scientific plans and instrumentation for the proposed EIC; and train students in nuclear science. The Request will also enable scientists to continue to fabricate the sPHENIX MIE for the study of high rate particle jets. The Request will also support modest and cost effective upgrades at STAR in preparation for a polarized proton run in 2022. U.S. scientists will participate in the highest priority heavy ion efforts at the international ALICE, CMS, and ATLAS LHC experiments, and the request will support upgrades at these facilities. The Request will support targeted accelerator R&D relevant to NP programmatic needs. The FY 2021 Request also will support the new SC Strategic Accelerator Technology Initiative. | Funding will support the core scientific workforce at universities and national laboratories to conduct research at RHIC, the LHC, and for EIC detector development. U.S. contributions to the LHC "common funds," fees to support individual U.S. scientist participation in the LHC program and the use of LHC computing capabilities, are deferred until FY 2022. The first year of funding for the Strategic Accelerator Technology Initiative will be supported within the NP Medium Energy and Heavy Ion subprograms. |

(dollars in thousands)

| FY 2020 Enacted | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|
| Operations $196,651 | $194,928 | -$1,723 |
| RHIC operates for 3,260 hours (88 percent of optimum) and focuses on the beam energy scan, including the newly implemented Low Energy RHIC Electron Cooling to increase luminosity of low energy beams. Funding supports the RHIC accelerator complex, including mission readiness and development of the experimental halls and instrumentation, mission readiness of the suite of accelerators, all power and consumables of the site, cryogenics plant, high priority facility and instrumentation capital equipment, high priority accelerator improvement projects, and the key computing capabilities for data taking and analysis. Support is provided to maintain critical core competencies and essential accelerator scientists, engineers, and technicians, and RHIC operations staff. The sPHENIX MIE, which will enable the study of high rate particle jets, receives operations funding in accordance with the planned profile. Accelerator scientists participate in high priority accelerator R&D. | The Request will support RHIC operations for 2,580 hours (100 percent optimal). Operating hours of 2,580 are lower than the typical hours RHIC can operate, however, the operating hours are capped in FY 2021 due to planned installation requirements. ). The Request also will support the RHIC accelerator complex, including mission readiness and development of the experimental halls and instrumentation, mission readiness of the suite of accelerators, all power and consumables of the site, cryogenics plant, activities to reduce helium consumption, high priority facility and instrumentation capital equipment, high priority accelerator improvement projects, and computing capabilities for data taking and analysis. Support will maintain critical core competencies and accelerator scientists, engineers, and technicians, for RHIC operations and EIC design. Limited operations funding will be redirected to the sPHENIX MIE, which will study high rate particle jets. Accelerator scientists will participate in high priority accelerator R&D. | Funding supports maximum operations of RHIC, which require reduced operating hours (2,580 hours) to accommodate installation requirements at the facility. Funding continues for the sPHENIX MIE. |
| Other Project Costs $10,000 | $1,500 | -$8,500 |
| Funding provides the first year of Other Project Costs (OPC) for the EIC, aimed at research to reduce technical risk and the development of a conceptual design. While requested in the Theory subprogram in FY 2020, with a site selection of BNL announced in January 2020, the funding is now included in the Heavy Ion Program. | The Request will provide for OPC for the EIC, aimed at research to reduce technical risk and the development of a conceptual design. | Funding will continue for OPC funding for EIC. |

## Nuclear Physics
## Low Energy Nuclear Physics

### Description

The Low Energy Nuclear Physics subprogram includes two scientific subprograms that focus on using nuclear interactions and decays to answer overarching questions related to 1) Nuclear Structure and Nuclear Astrophysics, and 2) Fundamental Symmetries.

### Nuclear Structure and Nuclear Astrophysics

Questions associated with Nuclear Structure and Nuclear Astrophysics include:

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the nature of neutron stars and dense nuclear matter?
- What are the origins of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?

The Nuclear Structure and Nuclear Astrophysics subprogram addresses these questions through support of research to develop a comprehensive description of nuclei using beams of stable and rare isotopes to yield new insights and reveal new nuclear phenomena. The subprogram also measures the cross sections of the nuclear reactions that power stars and lead to spectacular stellar explosions, which are responsible for the synthesis of the elements.

The ATLAS scientific user facility at ANL is the DOE-supported facility providing research opportunities in Nuclear Structure and Nuclear Astrophysics, serving approximately 350 domestic and international scientists per year. ATLAS is the world's premiere facility for stable beams and provides high-quality beams of all the stable elements up to uranium, as well as selected beams of short-lived (radioactive) nuclei to study nuclear properties under extreme conditions and reactions of interest to nuclear astrophysics, using the Californium Rare Ion Breeder Upgrade (CARIBU) ion source. Technologically cutting-edge and unique instrumentation are a hallmark of the facility, and ATLAS continues to be significantly oversubscribed by the user community. ATLAS is also an essential training ground for scientists and students. The facility nurtures an expert core competency in accelerator science with superconducting radio frequency cavities for heavy ions that are relevant to next generation high-performance proton and heavy ion linacs. This competency is important to the SC mission and international stable and radioactive ion beam facilities. ATLAS stewards a target development laboratory, the National Center for Accelerator Target Science, a national asset for the low energy community, including FRIB.

FRIB, under construction at Michigan State University (MSU), will advance understanding of rare nuclear isotopes and the evolution of the cosmos by providing beams of rare isotopes with neutron and proton numbers far from those of stable nuclei in order to test the limits of nuclear existence. The Gamma-Ray Energy Tracking Array (GRETA) MIE is one of the primary tools that the nuclear science community has identified necessary to leverage the capabilities of FRIB. GRETA's unprecedented combination of full coverage with high efficiency, and excellent energy and position resolution, will extend the reach of FRIB's ability to study the nuclear landscape, provide new opportunities to discover and characterize key nuclei for electric dipole moment searches, and open new areas of study in nuclear astrophysics. The High Rigidity Spectrometer (HRS) will specifically exploit FRIB's fast beam capabilities and enabling the most sensitive experiments across the entire chart of nuclei with the most neutron-rich nuclei available.

Scientists participate in the international effort to discover and characterize new "super heavy" elements in the periodic table. U.S. researchers played a prominent role in the recent discovery of Elements 115, 117, and 118, and Element 117 was named Tennessine to acknowledge the leadership role of the U.S. in these efforts. Research is ongoing to characterize these new elements and also to discover Elements 119 and 120. All of these past and future experiments were/are made viable by the provision of rare isotopes produced at HFIR through the DOE Isotope Program. NP also supports operations of the LBNL 88-Inch Cyclotron to provide beams for a small in-house nuclear science program focused on studying the properties of newly discovered elements on the periodic table, as well as conducting independent searches for new elements. DOD and NASA exploit materials irradiation capabilities at the 88 Inch to develop radiation-resistant electronics for their missions.

There are three university Centers of Excellence within the Low Energy subprogram, each with specific goals and unique physics programs: the Cyclotron Institute at Texas A&M University (TAMU), the accelerator facility at the TUNL at Duke University, and unique expertise and capabilities for instrumentation development at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington.

**Fundamental Symmetries**

Questions related to Fundamental Symmetries of nature addressed in low energy nuclear physics experiments include:

- What is the nature of neutrinos, what are their masses, and how have they shaped the evolution of the cosmos? What experimental approach for a next generation, ton-scale neutrino-less double beta decay (NLDBD) detector is capable of achieving the sensitivity necessary to determine if the neutrino is its own anti-particle?
- Why is there now more matter than antimatter in the universe? Is there evidence from the electric-dipole moments of atomic nuclei and the neutron that indicate our current understanding of the fundamental laws governing nuclear physics is incomplete?
- Will precise measurements in electron scattering and the decay of nuclei indicate forces present at the dawn of the universe that disappeared from view as the universe evolved?

The Fundamental Symmetries portfolio addresses these questions through precision studies using neutron beams and decays of nuclei, including beta decay, double-beta decay, and NLDBD, and electron beams. U.S. scientists are world leaders in the global research effort aimed at neutrino science and owing to the importance of nuclear beta decay in understanding neutrino properties, NP is the steward of neutrino mass measurements and NLDBD in SC. Often in partnership with NSF, NP has invested neutrino experiments both domestically and overseas, playing critical roles in international experiments that depend on U.S. leadership for their ultimate success (Cryogenic Underground Observatory for Rare Events (CUORE), KATRIN), and R&D of candidate technologies for next–generation experiments, including germanium (LEGEND), xenon (nEXO) and molybdenum (CUPID). In partnership with NSF, NP participates in the international LEGEND-200 experiment. The NSAC 2015 LRP recommended "the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment." NLDBD can only occur if neutrinos are their own anti-particles and such events would have profound, game changing consequences for the present understanding of the physical universe. The Ton-Scale NLDBD MIE is expected to provide unprecedented resolution for the detection of the rare process; the MIE received CD-0, Approval of Mission Need, in November 2018.

Very precise measurements in parity violating electron scattering, the decay of nuclei, and the properties of neutrons provide sensitivity to new forces and address questions about the matter/anti-matter imbalance rivaling, and even exceeding, the reach of high energy colliders. The MOLLER MIE will measure the parity-violating asymmetry in electron-electron scattering at CEBAF which is uniquely sensitive to the possible existence of new as yet unforeseen particles. Evidence for electric dipole moments of the neutron and atoms violate time reversal invariance and would shed light on the matter/anti-matter imbalance in the universe. Beams of cold and ultracold neutrons with the dedicated Fundamental Neutron Physics Beamline (FNPB) at the SNS are used to study fundamental properties of neutrons, including the flagship experiment to measure the electric dipole moment of the neutron.

Nuclear Structure and Nuclear Astrophysics Research
This activity supports high priority research groups at ANL, LBNL, LLNL, and ORNL and at universities. Scientists develop, fabricate, and use specialized instrumentation at ATLAS, and participate in the acquisition and analysis of data. Scientists participate in the design and fabrication of instrumentation for FRIB and development of upcoming scientific program. Funds transition key scientists that used to be supported by NSF at the National Superconducting Cyclotron Laboratory (NSCL) to this DOE portfolio to support the FRIB scientific mission. The Request continues funding for the GRETA MIE and maintains the HRS project. Scientists participate in research to characterize and discover new super-heavy elements at international facilities and the 88 Inch cyclotron. The Request will provide support to the university Centers of Excellence at TUNL and TAMU for the conduct of nuclear structure and nuclear astrophysics experiments at these niche facilities.

Fundamental Symmetries Research
The activity supports high priority research at BNL, LANL, LBNL, LLNL, ORNL, PNNL, and SLAC, and at universities. R&D for a challenging experiment to measure the electric dipole moment of the neutron, which could shed light on the asymmetry of matter versus antimatter in the universe, and other experiments at the SNS FNPB continue. First-generation NLDBD experiments continue to acquire data, such as the CUORE experiment at Gran Sasso Laboratory in Italy. Conceptual design efforts continue for an international ton-scale NLDBD MIE, along with targeted R&D. Scientists at TJNAF continue to implement the MOLLER MIE. Scientists participate in the operations of the KATRIN experiment at the Karlsruhe Institute of Technology in Karlsruhe, Germany to provide a measurement of the neutrino mass. University Centers of Excellence at TUNL, CENPA, and TAMU with unique capabilities are exploited to advance research in Fundamental Symmetries.

Nuclear Structure and Nuclear Astrophysics Operations
The activity supports facility and operations costs associated with ATLAS, FRIB, and the 88-Inch Cyclotron. ATLAS provides highly reliable and cost-effective stable and selected radioactive beams and specialized instrumentation. Funding provides support for the operations and power costs of the ATLAS, and targeted support for high priority accelerator and scientific instrumentation capital equipment, accelerator improvement projects, and experimental support. ATLAS efficiency and complexity has been increasing with the addition of the Electron Beam Ion Source (EBIS), the cutting edge CARIBU radioactive beam system for accelerated radioactive ion beams, the in-flight radioactive ion separator to increase the intensity of radioactive beams, and a gas-filled analyzer.

The ATLAS facility nurtures a core competency in accelerator science with superconducting radio frequency cavities for heavy ions that are relevant to the next generation of high-performance proton and heavy ion linacs. This competency is important to the Office of Science mission and international stable and radioactive ion beam facilities. Critical efforts continue to address facility oversubscription and increase available beam time, with development of the cost-effective multi-user upgrade Accelerator Improvement Project which will significantly increase the beam hours available for experiments to the scientific community.

The Request includes funding to support FRIB operations in advance of the first year of operations in FY 2022. The funds retain the most critical operations staff as accelerator components are completed on the project and direct their efforts towards the transition to operations, including commissioning, system tests, and developing operational performance of systems.

The Request also sustains operations of the 88-Inch Cyclotron for a focused in-house nuclear physics program which includes characterization and searches for new elements and nuclear data measurements.

## Activities and Explanation of Changes

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| **Low Energy Nuclear Physics** | **$126,737** | **$110,577** | **-$16,160** |
| Research | $70,998 | $60,336 | -$10,662 |
| Funding supports focused university and laboratory nuclear structure and nuclear astrophysics efforts at ATLAS, the world's premiere stable beam facility, and development of the FRIB scientific program. As NSCL staff transition to FRIB, funding is provided to transition scientific personnel from NSF to DOE support. Research continues at the unique university-based Centers of Excellence at TUNL, CENPA and TAMU. Scientists participate in first generation NLDBD experiments. The ton-scale NLDBD and MOLLER MIEs are initiated. Scientists participate in the international KATRIN. Funding continues for the GRETA MIE. The HRS MIE for FRIB is initiated. | | The Request will support high priority university and laboratory nuclear structure and nuclear astrophysics efforts at ATLAS and development of the FRIB scientific program. of the Request includes research support for FRIB scientific personnel. The Request will continue funding for the GRETA and HRS MIEs. Scientists will participate in the characterization of recently discovered elements and search for new ones. Research will continue at the university-based Centers of Excellence at TUNL, CENPA, and TAMU.<br><br>High priority research in NLDBD will continue with CUORE, LEGEND-200, and nEXO. The Request will continue the ton-scale NLDBD MIE and the MOLLER MIE. The Request will continue support for U.S. participation in the operations of the international KATRIN experiment. | Support focuses on high priority efforts and essential workforce at universities and national laboratories. Funding for the ton-scale NLDBD MIE is increased slightly. Funding for the GRETA and Moller MIEs are decreased. |

(dollars in thousands)

| FY 2020 Enacted | FY 2021 Request | Explanation of Changes<br>FY 2021 Request vs FY 2020 Enacted |
|---|---|---|
| Operations $55,739 | $50,241 | -$5,498 |
| Funding supports operation of ATLAS to address the high demand for ATLAS beam time, which continues to far exceed availability. ATLAS funding at this cost-effective facility will support 5,950 hours of beam time, operations staff, maintenance, and accelerator improvement projects and capital equipment for the facility and scientific instrumentation, including an upgrade to CARIBU. Funding also sustains operations of the LBNL 88-Inch Cyclotron. Funding provides FRIB with support for activities and transition staff from the construction effort to FRIB operations. | The Request will support operations of ATLAS at 2,980 hours (44 percent of optimal), and will provide funding for staff, maintenance, and high priority accelerator improvement projects and capital equipment for the facility and scientific instrumentation, including the development of a multi-user capability. Funding will sustain operations of the 88-Inch Cyclotron for high priority experiments studying newly discovered elements. The Request will support high priority activities necessary to prepare for FRIB operations in FY 2022. | Funding supports high priorities in the program, offset by reduced operations support for FRIB, ATLAS, and the LBNL 88-Inch Cyclotron. |

**Nuclear Physics**
**Nuclear Theory**

**Description**

The Nuclear Theory subprogram provides the theoretical support needed to interpret the wide range of data obtained from the experimental nuclear science subprograms and to advance new ideas and hypotheses that identify potential areas for future experimental investigations. One major theme of theoretical research is the development of an understanding of the mechanisms and effects of quark confinement and deconfinement. A quantitative description of these phenomena through QCD is one of this subprogram's greatest intellectual challenges. New theoretical and computational tools are also being developed by the community to describe nuclear many-body phenomena; these approaches will likely also see important applications in condensed matter physics and in other areas of the physical sciences. Another major research area is nuclear astrophysics, which includes efforts to understand the origins of the elements and the consequences that neutrino masses have for nuclear astrophysics.

This subprogram supports the Institute for Nuclear Theory (INT) at the University of Washington. It also supports topical collaborations within the university and national laboratory communities to address only the highest priority topics in nuclear theory that merit a concentrated theoretical effort.

The U.S. Nuclear Data Program (USNDP) aims to provide current, accurate, and authoritative data to workers in basic and applied areas of nuclear science and engineering. It addresses this goal primarily through maintaining and providing public access to extensive nuclear physics databases, which summarize and cross-correlate the results of over 100 years of research on nuclear science. These databases are an important national and international resource, and they currently serve approximately four and a half million retrievals of nuclear data annually. The USNDP also addresses important gaps in nuclear data through targeted experiments and the development and use of theoretical models. The program involves the combined efforts of approximately 50 nuclear scientists at 10 national laboratories and universities, and is managed by the National Nuclear Data Center (NNDC) at BNL. The USNDP provides evaluated cross-section and decay data relevant to a broad suite of federal missions and topics. NP leads an interagency working group including NNSA, NE, the DOE IP, and other federal agencies to coordinate targeted experimental efforts.

Nuclear physicists participate in activities related to QIS and quantum computing (QC), in coordination with other SC research programs. NP-specific efforts include R&D on quantum sensors to enable precision NP measurements, development of quantum sensors based on atomic-nuclear interactions, and development of quantum computing algorithms applied to quantum mechanical systems and NP topical problems. In support of the National Quantum Initiative, SC QIS Center(s) that will be established in FY 2020 will constitute an interdisciplinary partnership among SC Program Offices, including NP. Support for the SC QIS centers continues in FY 2021.

Scientists will develop cutting-edge techniques based on AI/ML of relevance to nuclear science research, accelerator facility operations and automated machine operations in the DOE IP. NP has been supporting applications of artificial neural networks in the analysis of nuclear physics data for decades. Additionally, NP is supporting technical development at the intersections between real-time ML and control and the optimization of accelerator systems operations and detector design using AI models. Future "intelligent" experiments will seek to incorporate next generation AI hardware and electronics into detector systems. NP also supports researchers engaged in developing learning techniques focused on improving efficiencies of accelerator operations.

The Nuclear Theory subprogram supports and leverages LQCD calculations that are critical for understanding and interpreting many of the experimental results from RHIC, LHC, and CEBAF. NP supports LQCD computing needs for dedicated computational resources with investments at TJNAF.

The Nuclear Theory subprogram also supports SciDAC, a collaborative program with ASCR that partners scientists and computer experts in research teams to address major scientific challenges that require supercomputer facilities performing at current technological limits. The NP SciDAC program operates on a five-year cycle, and supports computationally intensive research projects jointly with other SC and DOE offices in areas of mutual interest.

Theory Research

This activity supports targeted, high priority research at seven national laboratories (ANL, BNL, LANL, LBNL, LLNL, ORNL, and TJNAF). This research advances our fundamental understanding of nuclear physics, interpreting the results of experiments carried out under the auspices of the experimental nuclear physics program, and identifies and explores compelling new areas of research. The Request supports a new cohort of topical collaborations within available funds to bring together theorists to address specific high-priority theoretical challenges. The activity supports high priority efforts on FRIB theory, which is critical to theory research associated with the planned FRIB scientific program in order to optimize the interpretation of the experimental results.

The Request supports increases for research related to QIS and QC to provide technological and computational advances relevant to NP and other fields. Following exploratory QIS/QC workshops at the Institute for Nuclear Theory and at ANL, as well as a QC "test-bed" simulation to demonstrate proof-of-principle use of quantum computing for scientific applications, the NSAC published a report[a] in October 2019 to articulate further priority areas in QIS/QC where unique opportunities exist for nuclear physics contributions. For example, the report noted that the intersection of Quantum Field Theory and QC was an exciting opportunity for important advances achieved through nuclear physics research.

SciDAC-4 awards selected in FY 2017 continue as planned in FY 2021, with progress monitored via peer review. In addition to addressing specific problems relevant for nuclear physics research, SciDAC-4 projects continue to serve as a water-shed for training scientists who can address national needs.

Funding for a new AI/ML initiative is requested within the Nuclear Theory subprogram in FY 2021, which will support efforts throughout NP. The AI/ML Initiative will provide targeted investments to develop cutting-edge techniques based on AI of relevance to nuclear science research, accelerator facility operations, and automated machine operations.

The Request also includes funding to support the most essential activities of the USNDP to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. In addition to improving the completeness and reliability of data already archived that is used for industry and for a variety of Federal missions, NP funding enables targeted experiments to address gaps in the data archives deemed of high priority and urgency. Examples of targeted measurements include gamma ray spectroscopy of relevance for medical isotope science; nuclear beta decay data and reactor decay heat data of relevance for optimizing the emergency cooling systems of nuclear reactors and for the control of fast breeder reactors, anti-neutrino data relevant for basic research, and uranium-238 cross section data using neutron-gamma coincidences important for several Federal missions. Experimental measurements targeted by NP for funding are carried out in coordination with projects funded by other Federal offices in response to the annual joint Funding Opportunity Announcement for Nuclear Data issued by the NP-led Inter-Agency Nuclear Data Working Group.

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[a] "*Nuclear Physics and Quantum Information Science*" Nuclear Science Advisory Committee, October 2015 (https://science.osti.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf).

**Activities and Explanation of Changes**

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| **Nuclear Theory** | **$51,862** | **$54,266** | **+$2,404** |
| Theory Research | $43,062 | $46,540 | +$3,478 |
| Funding supports high priority QIS efforts. LQCD computing hardware investments are supported at TJNAF. Funding supports high priority theoretical research at universities and national laboratories for the interpretation of experimental results obtained at NP facilities, and the exploration of new ideas and hypotheses that identify potential areas for future experimental investigations. Theorists focus on applying QCD to a wide range of problems from nucleon structure and hadron spectroscopy, through the force between nucleons, to the structure of light nuclei. Advanced dynamic calculations to describe relativistic nuclear collisions and nuclear structure and reactions continue to focus on activities related to the research program at the upgraded 12 GeV CEBAF facility, the planned research program at FRIB, and ongoing and planned RHIC experiments. Funding supports the fourth year of SciDAC-4 grants and the final year of theory topical collaborations initiated in FY 2017. | | The Request will support high priority QIS efforts. LQCD computing investments continue at TJNAF. Funding will support high priority theoretical research at universities and national laboratories for the interpretation of experimental results obtained at NP facilities, and the exploration of new ideas and hypotheses that identify potential areas for future experimental investigations. Theorists will focus on applying QCD to a wide range of problems from nucleon structure and hadron spectroscopy, through the force between nucleons, to the structure of light nuclei. Advanced dynamic calculations to describe relativistic nuclear collisions and nuclear structure and reactions will continue to focus on activities related to the research program at the upgraded 12 GeV CEBAF facility, the planned research program at FRIB, and ongoing and planned RHIC experiments. The Request will support the fifth and final year of SciDAC-4 grants and the final year of theory topical collaborations initiated in FY 2017. Funding will target investments in an initiative to develop cutting-edge AI techniques of relevance to nuclear science research, accelerator facility operations, and automated machine operations. | The increase in funding will support QIS research, reflecting the growing importance of this field in nuclear physics, and a new initiative in AI/ML. |

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes<br>FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| Nuclear Data | $8,800 | $7,726 | -$1,074 |
| Funding supports the high priority USNDP efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. Funding also supports some critical experimental measurements to address gaps in existing nuclear data. | | The Request will provide support for high priority USNDP efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. The Request will also provide funding for critical experimental measurements to address gaps in existing nuclear data. | Funding continues for the high priority experimental nuclear data efforts. |

**Nuclear Physics**
**Isotope Development and Production for Research and Applications[a]**

**Description**

The Isotope Development and Production for Research and Applications subprogram (DOE Isotope Program, or DOE IP) supports the production, distribution, and development of production techniques for radioactive and stable isotopes in short supply and critical to the Nation. Isotopes are commodities of strategic importance for the Nation that are essential for energy exploration and innovation, medical applications, national security, and basic research. The goal of the program is to make key isotopes more readily available to meet U.S. needs and mitigate U.S. dependence on foreign supplies of isotopes. To achieve this goal, the program incorporates all isotope related R&D and production capabilities, including facilities and technical staff, required for supply chain management of critically important isotopes. The subprogram also supports R&D efforts associated with developing new and more cost-effective and efficient production and processing techniques, and on the production of isotopes needed for research purposes. The R&D activities provide collateral benefits for training, contributing to workforce development, and helping to ensure a future U.S.-based expertise in the fields of nuclear chemistry and radiochemistry. These disciplines are foundational not only to radioisotope production, but to many other critical aspects of basic and applied nuclear science as well.

All funding for DOE IP is executed through the Isotope Production and Distribution Program revolving fund. The isotope revolving fund maintains its financial viability by utilizing the appropriations for this subprogram along with revenues from the sale of isotopes and services. These resources are used to maintain the staff, facilities, and capabilities at user-ready levels and to support peer-reviewed R&D activities related to the production of isotopes. Isotopes sold to commercial customers are priced to recover the full cost of production, or the market price (whichever is higher). Research isotopes are sold at a reduced price to ensure that the high priority research requiring them does not become cost prohibitive. DOE IP makes investments in new capabilities to meet the growing demands of the Nation and foster future research in applications that will support national security and the health and welfare of the public.

Isotopes are critical national resources used to improve the accuracy and effectiveness of medical diagnoses and therapy, to enhance national security, to improve the efficiency of industrial processes, and to provide precise measurement and investigative tools for materials, biomedical, archeological, and other research. Some examples of produced isotopes are:

- actinium-225, actinium-227, tungsten-188, lutetium-177, strontium-89, strontium-90, and cobalt-60 for cancer therapy;
- americium-241 and californium-252 for oil and gas exploration and production well logging;
- bismuth-213, lead-212, astatine-211, copper-67, thorium-227, and radium-223 for cancer and infectious disease therapy and research; cadmium-109 for X-ray fluorescence imaging and environmental research;
- berkelium-249, americium-243, plutonium-242, californium-251, einsteinium-255, and curium-248 for use as targets for discovery of new super heavy elements;
- fermium-257 for heavy element chemistry research;
- selenium-75 for industrial radiography;
- nickel-63 for explosives detection, and lithium-6 and helium-3 for neutron detectors for homeland security applications; and
- arsenic-73, iron-52, and zinc-65 as tracers in metabolic studies.

Research to support the DOE Isotope Initiative builds upon existing core competencies in the DOE IP to grow expertise and enhance capabilities that promote U.S. independence in isotope supply and leadership in advanced isotope production technology, which does not necessitate immediate sale of product to be viable, enabling longer term and high-risk, high pay-off endeavors. Activities include the establishment of “not for sale” reserves of critical isotopes to mitigate unanticipated disruptions in foreign supply; development of transformative isotope production core competencies; exploration of isotope production techniques used globally; and pursuit of innovative, next-generation technology for

[a] All appropriations for the Isotope Development and Production for Research and Applications subprogram fund a payment into the Isotope Production and Distribution Program Fund as required by Public Law (P.L.) 101–101 and as modified by P.L. 103–316.

development of long-term product availability. This activity involves partnerships with NNSA, the Office of Nuclear Energy (NE), and other federal agencies.

Stable and radioactive isotopes are vital to the missions of many Federal agencies including the National Institutes of Health (NIH), National Institute of Standards and Technology (NIST), Department of Agriculture, Department of Homeland Security (DHS), NNSA, and other SC programs. The DOE IP continues to work in close collaboration with all federal organizations to develop strategic plans for isotope production and to forecast isotope needs and leverage resources. The DOE IP conducts biennial workshops, attended by representatives of all Federal agencies that require stable and radioactive isotopes, to provide a comprehensive assessment of national needs for isotope products and services, to inform priorities for investments in research for developing new isotope production and processing techniques, to communicate advances in isotope production research and availability, and to communicate concerns about potential constrained supplies of important isotopes to the Federal complex. The DOE IP participates in a number of Federal Working Groups and Interagency groups to promote communication, including the White House Office of Science and Technology Policy (OSTP) National Science and Technology Committee Subcommittee on Critical and Strategic Mineral Supply Chains, and the Interagency Group on Helium-3 (He-3), which it leads and that reports to the White House National Security Staff. The DOE IP participates in the Certified Reference Material Working Group which ensures material availability for nuclear forensics applications that support national security missions and also the Nuclear Regulatory Commission Task Force on Radiation Source Protection and Security. As a service, the DOE IP collects demand and usage information on helium-4 from the federal complex and provides it to the Bureau of Land Management (BLM) so that BLM can optimize their plans for the helium-4 federal reserve.

The DOE IP supports innovative research to develop new or improved production and separation techniques for high priority isotopes in short supply. Priorities in isotope production research are informed by guidance from NSAC as described in the 2015 Long Range Plan for the DOE IP published in July 2015 under the title "Meeting Isotope Needs and Capturing Opportunities for the Future[a]." Emphasis is placed on providing training opportunities to students and post-docs to help assure a vibrant workforce essential to the technologies associated with isotope production. The DOE IP also invests in the Nation's future nuclear chemistry and biomedical researchers through support for the Nuclear Chemistry Summer School (NCSS) program. The NCSS, jointly supported with SC's BES program, consists of an intensive six-week program of formal accredited lectures on the fundamentals of nuclear science, radiochemistry, and their applications in related fields, as well as laboratory practicums focusing on state-of-the-art instrumentation and technology used routinely in basic and applied nuclear science.

The DOE IP is the steward of the Isotope Production Facility (IPF) at LANL, the Brookhaven Linac Isotope Producer (BLIP) facility at BNL, the Enriched Stable Isotope Prototype Plant (ESIPP) at ORNL, and hot cell facilities for processing and handling irradiated materials and purified products at ORNL, BNL, and LANL. Funding provides mission readiness for isotope production at all of these facilities and the Low Energy Accelerator Facility (LEAF) at ANL. Isotope production is also supported at other sites, such as the High Flux Isotope Reactor (HFIR) at ORNL for the production of californium-252, actinium-227 and many other reactor-produced radioactive isotopes, the Idaho National Laboratory Advanced Test Reactor (ATR) for the production of cobalt-60, PNNL for processing and packaging strontium-90, the Y-12 National Security Complex for processing and packaging lithium-6 and lithium-7, the LANL Plutonium Facility for extracting americium-241 from NNSA plutonium processes, and the Savannah River Site for the extraction and distribution of He-3. The DOE IP also supports a network of university facilities for cost-effective production of unique isotopes for research and industry.

Because the U.S. inventory is limited or has even been depleted in the cases of some specific isotopes, the U.S. is dependent on foreign sources for supplies of certain stable isotopes. The DOE IP has developed and implemented modern stable isotope enrichment devices to provide the Nation with enrichment capabilities that were absent since the DOE calutrons ceased operation in 1998. The ESIPP operates at ORNL to produce research quantities of enriched stable isotopes using gas centrifuge and electromagnetic ion separation technology. The Stable Isotope Production Facility (SIPF) MIE adds additional gas centrifuge capability and the new Stable Isotope Production and Research Center (SIPRC) enables the establishment of multiple full scale production lines in each technology. These efforts mitigate U.S. dependence on foreign

[a] Report: https://science.osti.gov/-/media/np/nsac/pdf/docs/2015/2015_NSACI_Report_to_NSAC_Final.pdf

supply. The DOE IP participates in the QIS initiative within SC, and develops stable isotope production capabilities for isotopes of interest to next generation quantum computers.

While the DOE IP is not responsible for the production of molybdenum-99 (Mo-99), the most widely used isotope in diagnostic medical imaging in the Nation, it works closely with NNSA, the lead entity responsible for domestic Mo-99 production, offering technical and management support. Consistent with the National Defense Authorization Act for Fiscal Year 2013, DOE IP also oversees proceedings of the NSAC in response to a charge to annually assess progress by NNSA toward ensuring a domestic supply of Mo-99. Additionally, DOE IP participates in the international High-Level Group on the Security of Supply of Medical Isotopes lead by the Organisation for Economic Co-operation and Development.

The mission of the DOE IP is facilitated by the National Isotope Development Center (NIDC), located at ORNL, which interfaces with the user community and manages business operations involved in the production, marketing, sale, and distribution of isotopes.

Research

The research activity has two primary components: (1) support of R&D via competitive funding opportunity announcements open to both universities and national laboratories, and (2) the provision of core R&D funding to national laboratories and universities with expert competencies in isotope production and processing to nurture that technical expertise and accomplish high priority R&D. In FY 2021, core R&D is increased to strengthen core competencies at LANL, BNL, ORNL, PNNL, the University of Washington, and most recently at ANL and Michigan State University. The Request will increase support for ANL, where the newest addition to the portfolio of accelerators resides – the LEAF accelerator.  Years of research support from the DOE IP have enabled isotope production using photo-nuclear reactions at this high power electron linac, culminating in the recent announcement that the isotope copper-67 (a dual purpose diagnostic/therapeutic for cancer treatment) is now routinely available for clinical trials. Likewise, core R&D support is ramped up at Facility for Rare Isotope Beams (FRIB), where the laboratory is establishing capabilities to harvest isotopes. Efforts to create novel approaches to enable the provision of isotopes for targeted alpha therapy for cancer treatments and theragnostic isotopes (combined diagnostic and therapeutic applications) are enhanced at all sites. The DOE IP has become the world leader in the provision of alpha—emitting isotopes for cancer therapy.

Competitive R&D efforts are increased at universities and laboratories to support a myriad of activities focused on making novel and critical isotopes to the Nation for a suite of applications and research, and to develop pathways to promote U.S. independence in isotope supply. A high priority of the DOE IP remains the dedicated research effort to develop large scale production capabilities of actinium-225 (Ac-225), a high priority isotope that has shown stunning success in the treatment of diffuse cancers and infections; in the past, available quantities have limited clinical trials and applications. The DOE IP now routinely produces accelerator-produced Ac-225 and is ramping up research to develop efficient full-scale production and processing capabilities to enable sufficient supply of the isotope for cancer treatment. Research efforts have demonstrated that the accelerator produced Ac-225 functions equivalently to the material derived from the decay of thorium-229 which used to be the only viable source of small quantities of Ac-225. In coordination with NIH, samples of the isotope produced by the accelerator production approach were evaluated by several different researchers involved in medical applications research to confirm these results. The Request will increase funding for research to explore approaches for production of other isotopes for targeted alpha therapy and promising theragnostic isotopes.

Competitive research increases to continue ongoing and new efforts, including research to alleviate the current U.S. dependence on foreign sources of deuterium, which was last produced in the U.S. in 1981. Deuterium is used in the development, production, and sale of compounds used in chemistry, biomedical and diagnostic research, environmental analysis and physics. There are two pathways being investigated: (1) new and efficient production and (2) recovery of deuterium from heavy water. Research also addresses topics such as Li-7 enrichment for molton salt reactors, new sources of He-3 for cryogenics, critical nuclear data measurements, radioisotope enrichment technology, next generation targetry, and Np-236 production feasibility for nuclear forensics.

The DOE IP is developing renewed enrichment capability with both electromagnetic separators and gas centrifuges and is actively enriching isotopes. Research increases to enhance stable isotope enrichment capabilities as well as to enrich new isotopes. Every stable isotope enriched requires an independent research campaign. Current efforts focus on ytterbium-176 as feedstock for prostate cancer treatment, xenon-129 for polarized lung imaging, Mo-100 as feedstock for Mo-99 production, and isotopes of interest for quantum computing. In addition, as this technology tends to be dual-use; nurturing a core competency in this technology is vital to the Nation. R&D associated with purification and processing of the existing isotope inventory continues. Increased research also enables exploration of other enrichment technologies.

Operations
The Request will support personnel and infrastructure essential to ensure mission readiness for the production and processing of isotopes at a growing portfolio of production sites; the isotope production costs are paid by the customer. Operating and capital investments enable substantial and compelling enhancements to productivity or new production or processing capability, including recovery of valuable isotopes from legacy reactor targets (Mark 18A); development of enrichment capabilities for heavier stable isotopes; upgrades and operations of hot cell facilities at BNL, ORNL, LANL and universities to increase the quantity and reliability of radioisotope processing capabilities in order to support the growing demand for radioisotopes like Ac-225 and Lu-177; and infrastructure to support the fabrication and assembly of enrichment technology. In addition, funding will support implementation of Food and Drug Administration (FDA) regulatory requirements for production of isotopes used in FDA-approved pharmaceuticals. Efforts supported the development of a Drug Master File for the accelerator-produced material, submitted to the FDA in FY 2020, and efforts now look towards the development of other Drug Master Files. Mission readiness for reactor-produced actinium-227, the world's first source of new material, is enhanced. Actinium-227 decays to radium-223, which is used in new radiopharmaceutical drugs to treat prostate cancer. The provision of actinium-227 by the DOE IP ensures that prostate cancer patients can have a reliable supply of palliative care drugs.

The DOE IP is increasing funding for production and processing at universities with unique capabilities, such as the multi-particle clinical cyclotron at the University of Washington where full-scale production of astatine-211 was developed to support research into the use of the isotope in cancer therapy; and the University of Missouri Research Reactor which the DOE IP uses for the production of lutetium-177 for cancer therapy research, and selenium-75 for industrial gamma radiography. The establishment of a coordinated network of university-based isotope production was a recommendation in the 2015 NSAC-Isotope Long Range Plan. The network is designed to leverage the unique and often underutilized facilities available at academic institutions which are generally more suited to low-energy production reactions and can support nationwide availability of short-lived radioisotopes. Actions to include additional university sites in the network continue in FY 2021. The Request will increase funding to continue the addition of isotope harvesting at the FRIB.

DOE IP increases operations of ESIPP at ORNL to produce research quantities of enriched stable isotopes through the use of electromagnetic separation and centrifuge technology. The first campaign at ESIPP produced ruthenium-96 in FY 2018 to provide the otherwise unavailable world-wide target material to the RHIC for its planned physics program. ESIPP is now focused on production of Yb-176, currently only produced in Russia, needed for the production of Lu-177, which is used to treat prostate cancer. The DOE IP continues support for the development of production approaches for enriched stable isotopes of interest for future QIS-driven technologies.

The Request will provide funding for the DOE Isotope Initiative. Funding will be invested to explore and grow competence in stable isotope enrichment technologies beyond the current electromagnetic ion separation and gas centrifuge technologies to consider efficiencies in isotope production.

The SIPF MIE is adding additional gas centrifuge capability to the existing ESIPP; the last year of funding for SIPF was in FY 2020. No additional funding is required in FY 2021 for the SIPF MIE. Staff will participate in fabrication activities aiming towards a completion date of FY 2024. Developing modern enrichment technology is high-risk and challenging, and a phased approach in implementing technology is being pursued. Additional capabilities in both electromagnetic ion separation and gas centrifuge capability beyond SIPF and ESIPP are needed to meet the quickly rising demands of the Nation for enriched stable isotopes and fully mitigate U.S. dependence on foreign supply, and operate multiple production lines simultaneously. The Request will continue funding for the U.S. Stable Isotope Production and Research Center (U.S. SIPRC) project to meet those needs. Scientists and engineers are supported in FY 2020 to advance the Conceptual Design of U.S. SIPRC and prepare for CD-1. The Request will support staff to participate in design and long lead procurement activities for U.S. SIRPC.

**Activities and Explanation of Changes**

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| **Isotope Development and Production for Research and Applications** | **$49,500** | **$66,000** | **+$16,500** |
| Research | $11,500 | $22,000 | +$10,500 |
| Funding supports high priority competitive R&D activities at universities and national laboratories leading to new isotope production technologies. Support for core research groups at national laboratories and universities enhance isotope production capabilities specifically relevant to the physical resources and expertise available at the institution. Funding supports the development of two new core R&D groups, one at MSU to support the new isotope harvesting capability being established at FRIB, and the other at ANL to support the new isotope production effort at the LEAF electron facility at ANL. Research activities aimed at the development of production approaches for isotopes of interest to next-generation QIS systems continues. Research to develop enrichment capability for new isotopes of importance increases. | | The Request will support high impact R&D activities at universities and national laboratories leading to advanced and novel isotope production and processing technologies, to increase the availability of isotopes in short supply. Funding will increase for the new R&D groups at MSU for FRIB isotope harvesting, and at ANL to support the new isotope production effort at the LEAF. A priority of the research program will be to continue the development of full scale processing and technology for the production of alpha-emitters for cancer therapy, such as Ac-225. The Request will increase competitive R&D efforts at universities and laboratories to support a myriad of activities focused on making novel and critical isotopes to the Nation for a suite of applications and research, and to develop pathways to promote U.S. independence in isotope supply. The Request will also increase funding to expand theUniversity Isotope Network to perform the R&D necessary to enable routine production. Research activities aimed at the development of production approaches for isotopes of interest to next-generation QIS systems will continue. Research to develop enrichment capability for new isotopes of importance will increase. | The increase will support the strengthening of core research groups at national laboratories and universities to nurture unique core competencies and accomplish high priority R&D that addresses shortages of isotopes important to the nation. The increase also will establish research groups at the new production sites at ANL and MSU, and provides additional funding for research for enriched stable and radioisotope technology, such as therapeutic alpha-emitting isotopes like Ac-225. The increase also will provide additional funds for competitive R&D to consider new opportunities for improving or developing new and unique capabilities for isotope production and processing, enabling U.S. leadership in research and applications, such as discovery of new elements, forefront cancer treatments. Also, the increase provides additional funding for enriched stable isotope production R&D to enable new production campaigns of rare isotopes. |

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | Explanation of Changes FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|
| Operations | $38,000 | $44,000 | +$6,000 |
| Funding supports mission readiness of the isotope production facilities and nurtures critical core competencies in isotope production and development, ensuring that isotope orders for cancer therapy and other commitments are reliably met. The NIDC activities are increased to effectively interface with the growing stakeholder community and isotope portfolio. Funding expands operations of the University Isotope Production Network and ESIPP operations. Increased funding supports the development of production approaches for isotopes of interest for next generation QIS-driven technologies. Final funding is provided for the SIPF MIE, according to the planned profile. Investments support electromagnetic separation technology optimized to heavy elements, enriched radioisotope separation technology, modest upgrades at BLIP and the IPF for new capabilities, enhanced processing capabilities at universities and national laboratories, infrastructure for assembly and fabrication of stable enrichment components, and the initiation of isotope harvesting capabilities at FRIB. Other Project Costs for SIPRC are supported to advance the Conceptual Design and prepare for CD-1. | | The Request will support mission readiness of the isotope production facilities and nurtures critical core competencies in isotope production and development, ensuring that isotope orders for cancer therapy and other commitments are reliably met. Core competencies in isotope production and development will grow to ensure that isotope orders for cancer therapy and other commitments are reliably met. Support will maintain NIDC activities to interface with the growing stakeholder community and rapidly expanding isotope portfolio. Production approaches for isotopes of interest for next generation QIS-driven technologies will be maintained. Funding will continue support of electromagnetic separation technology optimized to heavy elements, enriched radioisotope separation technology, modest upgrades at BLIP and the IPF for new capabilities, enhanced processing capabilities at universities and national laboratories, infrastructure for assembly and fabrication of stable enrichment components, and ramp up of funding for isotope harvesting capabilities at FRIB. The Request will support the DOE Isotope Initiative with a focus on creating core competencies in developing and operating a broad array of isotope enrichment technologies, critical for research and applications. | The funding increase will support the DOE Isotope Initiative, which in FY 2021, explores and grow competence in stable isotope enrichment technologies beyond the current electromagnetic ion separation and gas centrifuge technologies to consider efficiencies in isotope production. The increase also will support the implementation of isotope harvesting at FRIB. |

## Nuclear Physics
## Construction

**Description**

This subprogram supports all line-item construction for the entire NP program. All Total Estimated Costs (TEC) are funded in this subprogram, including engineering, design, and construction. Other Project Costs (OPC) are funded in the relevant subprograms.

Consistent with the 2015 NSAC Long-Range Plan's highest priority, the FY 2021 Request includes funding to capitalize on NP's prior scientific facilities investments. Funding provides for design and construction of scientific research facilities needed to meet overall objectives of the Nuclear Physics program. NP currently has two ongoing projects, which receive construction line item funding in FY 2021. In addition, the DOE IP, managed by NP, also continues a line item construction project in FY 2021.

The FRIB at MSU will continue construction activities in FY 2021, with a funding request aligned to the current baseline. FY 2021 is the final budget request for FRIB. The project is proceeding on track within the established project baseline. FRIB will provide intense beams of rare isotopes for world-leading research opportunities in nuclear structure, nuclear astrophysics, and fundamental symmetry studies that will advance knowledge of the origin of the elements and the evolution of the cosmos. It offers a facility for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a broadly applicable theory of the structure of nuclei will emerge. FRIB will provide an essential scientific tool for over 1,400 scientists each year from across academic, industrial, and government institutions. The project is funded through a cooperative agreement with MSU. The project has a baseline DOE Total Project Cost (TPC) of $635,500,000.

The FY 2021 Request continues the construction effort for the Electron-Ion Collider (EIC). Since the 2002 LRP for Nuclear Science was developed and released, a compelling, persistent, high scientific priority for the U.S. nuclear science community has been understanding how the fundamental properties of the proton, such as its mass and spin, are dynamically generated by the extraordinarily strong color fields resulting from dense systems of gluons in nucleons and nuclei. The answer to this question is key to addressing an outstanding grand challenge problem of modern physics: how QCD, the theory of the strong force, which explains all strongly interacting matter in terms of points like quarks interacting via the exchange of gluons, acts in detail to generate the "macroscopic" properties of protons and neutrons. The 2015 LRP for Nuclear Science concluded, "…a high energy, polarized electron ion collider is the highest priority for new facility construction..." A National Academies study, charged to independently assess the impact, uniqueness, and merit of the science that would be enabled by U.S. construction of an electron ion collider, gave a strong endorsement to a U.S.-based EIC, and recognized its critical role in maintaining U.S. leadership in nuclear science and accelerator R&D. Scientists and accelerator physicists from both the Medium Energy and Heavy Ion subprograms are actively engaged in the development of the scientific agenda, design of the facility and development of scientific instrumentation related to a proposed EIC. Critical Decision-0 (CD-0), Approve Mission Need, was received on December 19, 2019. The Department selected and announced Brookhaven National Laboratory (BNL) as the site for the EIC on January 9, 2020. The Rough Order of Magnitude Total Project Cost range for the EIC project at CD-0 approval was $1.6 billion to $4.2 billion, with an updated post-site selection cost range of $1.6 billion to $2.6 billion.

The FY 2021 Request will continue design efforts for the U.S. Stable Isotope Production and Research Center (U.S. SIPRC) and support long lead procurements. The demand for enriched stable isotopes continues to grow substantially. Demand drivers include enriched stables isotopes for medical, national security and fundamental research projects. DOE produced a legacy inventory of enriched stable isotopes using the former Y-12 plant Calutrons from the 1940s to 1990s, until they were decommissioned. DOE's supply of certain key enriched stable isotopes has been depleted, making the U.S. increasingly dependent on foreign imports for enriched stable isotopes. With support from the DOE IP, ORNL is advancing production capabilities for these stable isotopes, primarily electromagnetic isotope separation (EMIS) and gas centrifuge (GC) technologies. Electromagnetic isotope separators can separate isotopes for many elements to very high purity and at lower production rates while gas centrifuge production cascades can produce much larger quantities of isotopes but is limited to those isotopes that have compatible feedstock chemicals. The prototype capabilities of the Enriched Stable Isotope Prototype Plant (ESIPP), developed through DOE IP-supported research, demonstrated the feasibility of new EMIS and GC technology. The ongoing Stable Isotope Production Facility (SIPF) MIE modestly increases GC production capability. U.S.

SIPRC further expands GC production capability and significantly increases EMIS production capability to meet the Nation’s growing demand for stable isotopes. SIPRC will mitigate the Nation’s dependence on foreign countries for stable isotope supply. CD-0, Approve Mission Need, was received on January 4, 2019. The current Total Project Cost (TPC) point estimate is $229,000,000 with an updated preliminary TPC range of $175,000,000 to $298,000,000 in preparation for CD-1 consideration.

**Activities and Explanation of Changes**

(dollars in thousands)

| FY 2020 Enacted | | FY 2021 Request | | Explanation of Changes FY 2021 Request vs FY 2020 Enacted | |
|---|---|---|---|---|---|
| **Construction** | **$53,000** | | **$18,300** | | **-$34,700** |
| 20-SC-51, U.S. Stable Isotope Production and Research Center (ORNL) | $12,000 | | $12,000 | | $— |
| Funding supports engineering design of the U.S. SIPRC and long lead procurements for known designs of technologies developed for prior efforts. | | The Request will support the continuation of engineering design of the U.S. SIPRC and long lead procurements, such as site preparations and materials for known designs of technologies developed under previous projects. | | Funding will support engineering design of the U.S. SIPRC project. | |
| 20-SC-52, Electron Ion Collider (EIC) | $1,000 | | $1,000 | | $— |
| Funding provides the first year of TEC funding for the EIC. The funds will be used for engineering and design to reduce technical risk after completion of the conceptual design. | | The Request will continue TEC funding for the EIC. The funds will be used for engineering and design to reduce technical risk after completion of the conceptual design. | | Funding will support ongoing engineering and design efforts. | |
| 14-SC-50, Facility for Rare Isotope Beams (FRIB) | $40,000 | | $5,300 | | -$34,700 |
| Funding continues to support the fabrication, assembly, and testing of cryomodules, as well as their installation within the FRIB linear accelerator located in the tunnel area. As portions of the linear accelerator nears completion, commissioning efforts will also continue in order to validate accelerator's performance according to project requirements. In addition, fabrication, assembly, installation and testing of the experimental technical systems will continue; project completion is planned in FY 2022. | | The Request will complete cryomodule installation, experimental systems installation, and testing. The funds will also continue commissioning efforts associated with technical components as they are completed. This is the final year of funding. Project completion is planned in FY 2022. | | Funding will support the final efforts necessary to complete the FRIB according to its performance baseline cost, schedule, and scope in FY 2022. | |

**Nuclear Physics**
**Capital Summary**

(dollars in thousands)

| | Total | Prior Years | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|---|---|---|
| **Capital Operating Expenses** | | | | | | |
| Capital Equipment | N/A | N/A | 38,025 | 35,392 | 26,660 | -8,732 |
| Minor Construction Activities | | | | | | |
| General Plant Projects (GPP) | N/A | N/A | 2,060 | 9,616 | 2,143 | -7,473 |
| Accelerator Improvement Projects (AIP) | N/A | N/A | 5,077 | 7,268 | 8,783 | +1,515 |
| **Total, Capital Operating Expenses** | **N/A** | **N/A** | **45,162** | **52,276** | **37,586** | **-14,690** |

**Capital Equipment**

(dollars in thousands)

| | Total | Prior Years | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|---|---|---|
| **Capital Equipment** | | | | | | |
| Major Items of Equipment | | | | | | |
| *Heavy Ion Nuclear Physics* | | | | | | |
| Super-PHENIX (sPHENIX) MIE[a] | 27,000 | N/A | 5,310 | 9,520 | 3,000 | -6,520 |
| *Low Energy Nuclear Physics* | | | | | | |
| Gamma-Ray Energy Tracking Array (GRETA) MIE | 52,000-65,000[b] | 5,700 | 6,600 | 6,600 | 2,500 | -4,100 |
| High Rigidity Spectrometer (HRS)[c] | 80,000-90,000 | N/A | — | 1,000 | 1,000 | — |
| Ton-Scale Neutrinoless Double Beta Decay MIE | 215,000-250,000 | N/A | — | 1,000 | 1,440 | +440 |
| MOLLER MIE | 25,000-28,000 | N/A | — | 2,000 | 300 | -1,700 |

[a] sPHENIX MIE will be funded through existing operations funding which would typically be used to operate the previous version of the detector, PHENIX; no new funds are required. This MIE has been baselined. The impact of the Request will be assessed upon a FY 2021 Appropriation.
[b] Total Project Cost range at CD-3a Approval.
[c] HRS will be funded through a cooperative agreement with MSU and is not a capital asset. The HRS has CD-0 approval.

| | (dollars in thousands) | | | | | |
|---|---|---|---|---|---|---|
| | Total | Prior Years | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
| *Isotope Development and Production for Research and Development* | | | | | | |
| Stable Isotope Production Facility (SIPF) MIE | 25,500-28,000 | 12,500 | 11,500 | 1,500 | — | -1,500 |
| Total, MIEs | N/A | 18,200 | 23,650 | 21,620 | 8,240 | -13,380 |
| Total, Non-MIE Capital Equipment | N/A | N/A | 14,375 | 13,772 | 18,420 | +4,648 |
| **Total Capital Equipment** | **N/A** | **N/A** | **38,025** | **35,392** | **26,660** | **-8,732** |

**Minor Construction Activities**

| | (dollars in thousands) | | | | | |
|---|---|---|---|---|---|---|
| | Total | Prior Years | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
| **General Plant Projects (GPP)** | | | | | | |
| Greater than or equal to $5M and less than $20M | | | | | | |
| End Station Refrigerator at TJNAF | 9,500 | — | — | 9,500 | — | -9,500 |
| Total GPPs (greater than or equal to $5M and less than $20M) | 9,500 | — | — | 9,500 | — | -9,500 |
| Total GPPs less than $5M[a] | N/A | N/A | 2,060 | 116 | 2,143 | +2,027 |
| **Total, General Plant Projects (GPP)** | **N/A** | **N/A** | **2,060** | **9, 616** | **2,143** | **-7,473** |
| **Accelerator Improvement Projects (AIP)** | | | | | | |
| Greater than or equal to $5M and less than $20M | | | | | | |
| RHIC Low Energy Electron Cooling | 8,321 | 8,321 | — | — | — | — |
| FRIB Isotope Harvesting[b] | 9,000-11,000 | N/A | — | 2,000 | 3,500 | +1,500 |
| Total, AIPs (greater than or equal to $5M and less than $20M) | N/A | N/A | — | 2,000 | 3,500 | +1,500 |
| Total, AIPs less than $5M | N/A | 3,652 | 5,077 | 5,268 | 5,283 | +15 |
| **Total, Accelerator Improvement Projects (AIP)** | **N/A** | **11,973** | **5,077** | **7,268** | **8,783** | **+1,515** |
| **Total, Minor Construction Activities** | **N/A** | **N/A** | **7,137** | **16,884** | **10,926** | **-5,958** |

[a] GPP activities less than $5M include design and construction for additions and/or improvements to land, buildings, replacements or additions to roads, and general area improvements.
[b] FRIB Isotope Harvesting will be funded through a cooperative agreement with MSU and is not a capital asset.

**Nuclear Physics**
**Major Items of Equipment Description(s)**

Heavy Ion Nuclear Physics MIE:

*Super Pioneering High Energy Nuclear Interaction Experiment (sPHENIX)*

sPHENIX directly supports the NP mission by using precision, high rate jet measurements to further characterize the quark-gluon plasma (QGP) discovered at RHIC in order to understand the anomalous energy loss observed in the QGP. sPHENIX will enable scientists to study how the near perfect QGP liquid with the lowest shear viscosity ever observed arises from the strongly interacting quarks and gluons from which it is formed. CD-0 was approved September 13, 2016 and Project Decision (PD)-2/3, which approves the performance baseline and start of construction, was approved in September 19, 2019 with a TPC $27,000,000. This MIE is funded within the existing funds for RHIC operations. Operating funds that are typically used to maintain and operate the PHENIX detector will be used to upgrade the detector. No funding beyond that provided for existing RHIC operations is required. sPHENIX adds electron and hadron calorimeters to the existing silicon tracking capabilities and makes use of a recycled solenoid magnet for a cost effective upgrade. The FY 2021 Request for sPHENIX of $3,000,000 is the third year of TEC funding.

Low Energy Nuclear Physics: Nuclear Structure and Nuclear Astrophysics MIEs:

*Gamma-Ray Energy Tracking Array (GRETA)*

GRETA directly supports the NP mission by addressing the goal to understand the structure of nuclear matter, the processes of nuclear astrophysics, and the nature of the cosmos. A successful implementation of this detector will represent a major advance in gamma-ray tracking detector technology that will impact nuclear science, as well as detection techniques in homeland security and medicine. GRETA will provide unprecedented gains in detection sensitivity, addressing several high priority scientific topics, including how weak binding and extreme proton-to-neutron asymmetries affect nuclear properties and how the properties of nuclei evolve with changes in excitation energy and angular momentum. GRETA will provide transformational improvements in efficiency, peak-to-total ratio, and higher position resolution than the current generation of detector arrays. In particular, the capability of reconstructing the position of the interaction with millimeter resolution will fully exploit the physics opportunities of FRIB. Without GRETA, FRIB will rely on existing instrumentation. In that event, beam-times necessary for the proposed experiments will be expanded significantly, and some proposed experiments will not be feasible at all. CD-0 for GRETA was approved September 15, 2015 and CD-1 was obtained October 4, 2017. CD-3a, which approves long lead procurements, was obtained August 16, 2018 with an estimated TPC of $52,000,000 - $65,000,000. The FY 2021 Request for GRETA of $2,500,000 is the fifth year of TEC funding.

*High Rigidity Spectrometer (HRS)*

The HRS at FRIB will increase the scientific potential of state-of-the-art and community-priority devices, such as GRETA, and other ancillary detectors. FRIB will be the world's premier rare-isotope beam facility producing a majority (approximately 80 percent) of the isotopes predicted to exist. Eleven of the 17 NSAC Rare Isotope Beam Taskforce benchmarks, which were introduced to characterize the scientific research of a rare-isotope facility, require the use of fast beams at FRIB. The scientific impact of the FRIB fast beam science program will be substantially enhanced (by luminosity gain factors of between two and one hundred for neutron-rich isotopes, with the largest gains for the most neutron-rich species) by construction of the HRS. The HRS will allow experiments with beams of rare isotopes at the maximum production rates for fragmentation or in-flight fission. This enhancement in experimental sensitivity provides access to critical isotopes not available otherwise. The 2015 NSAC LRP recognized that the "HRS…will be essential to realize the scientific reach of FRIB." The HRS will be funded through a cooperative agreement with MSU and is not a capital asset. CD-0 was approved November 2018 with a TPC range of $80,000,000 - $90,000,000. CD-1 approval is planned in 4Q 2020. The FY 2021 Request for the HRS of $1,000,000 is the second year of funding.

Low Energy Nuclear Physics: Fundamental Symmetries MIEs:

*Ton-Scale Neutrino-less Double Beta Decay (NLDBD) Experiment*

The Ton-Scale NLDBD Experiment, implemented by instrumenting a large volume of a specially selected isotope to detect neutrino-less nuclear beta decays (where within a single nucleus, two neutrons decay into two protons and two electrons with no neutrinos emitted), directly supports NP's mission to explore all forms of nuclear matter. NLDBD can only occur if neutrinos are their own anti-particles and the observation of "lepton number violation" in such neutrino-less beta decay events would have profound consequences for present understanding of the physical universe. For example, one exciting prospect is that the observation of NLDBD would elucidate the mechanism, completely unknown at present, by which the mass of the neutrino is generated. The observation of lepton number violation would also have major implication for the present day matter/anti-matter asymmetry which has perplexed modern physics for decades. In the current experimental outlook, through FY 2018 a number of demonstrator efforts using smaller volumes of isotopes and various technologies (bolometry in tellurium dioxide (TeO2) crystals, light collection in LXe, charge collection in enriched germanium-76) have been in progress for several years, and all are in the process of delivering new state-of-the-art lifetime limits for neutrino-less double beta decay which are of order a few times 1025 years. The goal of a next generation ton-scale experiment is to reach a lifetime limit of 1028 years. For reference, the "lifetime limit" discussed is the time one might have to wait to observe neutrino-less double beta decay if observing a single nucleus only. Fortunately, in the ton of isotope planned for the ton-scale neutrino-less double beta decay experiment there are many trillions of nuclei. Thus, such decays, if they exist, should be observable on a much more reasonable timescale (five to ten years) similar to other large modern physics experiments. CD-0 was approved in November 2018 with a TPC range of $215,000,000 - $250,000,000. The FY 2021 Request of $1,440,000 is the second year of TEC funding.

*Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER)*
The MOLLER experiment directly supports the NP mission by measuring the parity-violating asymmetry in polarized electron-electron (Møller) scattering. This extremely small asymmetry is predicted to be on the order of 35 parts per billion (ppb), which requires unprecedented experimental techniques employed for this experiment. CD-0 was approved December 2016 with an estimated Total Project Cost of $25,000,000 to $35,000,000. The proposed MOLLER experiment is an ultra-precise measurement of the weak mixing angle using Møller scattering which will improve on existing measurements by a factor of five, yielding the most precise measurement of the weak mixing angle at low or high energy anticipated over the next decade. This new result would be sensitive to the interference of the electromagnetic amplitude with new neutral current amplitudes as weak as approximately $10^{-3}$ $G_F$ (Fermi Factor) from as yet undiscovered dynamics beyond the Standard Model. The resulting discovery reach is unmatched by any proposed experiment measuring a flavor- and CP-conserving process over the next decade, and yields a unique window to new physics at MeV and multi-TeV scales, complementary to direct searches at high energy colliders such as the Large Hadron Collider (LHC). The MOLLER MIE, which was initiated in the Medium Energy subprogram prior to the establishment of a targeted portfolio in Fundamental Symmetries, transitions to the Low Energy subprogram in the FY 2021 Request. The FY 2021 Request for MOLLER of $300,000 is the second year of TEC funding.

Isotope Development and Production for Research and Applications MIE:
*Stable Isotope Production Facility (SIPF)*
SIPF will enhance production capability of stable enriched isotopes to the kilogram throughput to help mitigate the dependence of the U.S. on foreign suppliers and better meet the high demands for enriched stable isotopes for the Nation. This MIE will provide infrastructure and optimized centrifuge capability for isotopes of interest. Fabrication continues until the project's planned completion in FY 2024. There is a high demand for a domestic capability to produce enriched stable isotopes for basic research, medical and industrial applications. For example, foreign NLDBD experiments in nuclear physics and dark matter experiments in high-energy physics are interested in kg quantities of enriched stable isotopes, which are not available in the U.S. The accelerator production route for molybdemnum-99 (Mo-99), a critical medical isotope for cardiac imaging, which is being supported by NNSA, relies on a feedstock of enriched Mo isotopes, which are also not available domestically. Stable isotopic nuclides of heavier elements are used for agricultural, nutritional, industrial, ecological and computing applications could also be produced. CD-1/3a was approved in May 2018 with an estimated TPC range of $25,500,000-$28,000,000. No funding is requested for this MIE in FY 2021, as final funding was requested and provided in FY 2020. Fabrication continues until the project's planned completion in FY 2024. No funding is requested for this MIE in FY 2021, as final funding was requested and provided in FY 2020.

**Nuclear Physics**
**Construction Projects Summary**

(dollars in thousands)

| | Total | Prior Years | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|---|---|---|
| **14-SC-50, Facility for Rare Isotope Beams** | | | | | | |
| TEC | 635,500[a] | 514,700[b] | 75,000 | 40,000 | 5,300 | -34,700 |
| OPC | — | — | — | — | — | — |
| **TPC** | **635,500** | **514,700** | **75,000** | **40,000** | **5,300** | **-34,700** |
| **20-SC-51, U.S. Stable Isotope Production and Research Center** | | | | | | |
| TEC | 175,000-298,000 | — | — | 12,000 | 12,000 | — |
| OPC | — | — | 500 | 2,100 | — | -2,100 |
| **TPC** | **175,000-298,000** | **—** | **500** | **14,100** | **12,000** | **-2,100** |
| **20-SC-52, Electron Ion Collider[c]** | | | | | | |
| TEC | TBD | — | — | 1,000 | 1,000 | — |
| OPC | — | — | — | 10,000 | 1,500 | -8,500 |
| **TPC** | **TBD** | **—** | **—** | **11,000** | **2,500** | **-8,500** |
| **Total, Construction** | | | | | | |
| **TEC** | **TBD** | **TBD** | **75,000** | **53,000** | **18,300** | **-34,700** |
| **OPC** | **TBD** | **TBD** | **500** | **12,100** | **1,500** | **-10,600** |
| **TPC** | **TBD** | **TBD** | **75,500** | **65,100** | **19,800** | **-45,300** |

[a] This is the DOE TPC; MSU's cost share is $94,500,000 bringing the total project cost to $730,000,000. FRIB is funded with operating dollars through a Cooperative Agreement financial assistance award with a work breakdown structure (WBS) that is slightly different from typical federal capital assets. The WBS totals $730,000,000 including MSU's cost share. Because the WBS scope is not pre-assigned to DOE or MSU funds, DOE's baseline of $635,500,000 cannot be broken down between TEC and OPC.

[b] A portion of the PY funding was provided within the Low Energy subprogram. The FY 2014 appropriation established FRIB as a control point.

[c] The preliminary TPC at CD-0 approval was $1.6 billion to $4.2 billion. On January 9, 2020, DOE selected Brookhaven National Laboratory as the location for the EIC. This selection establishes a new cost range of $1.6 billion to $2.6 billion for the EIC.

**Nuclear Physics**
**Funding Summary**

| | (dollars in thousands) | | | |
|---|---|---|---|---|
| | **FY 2019 Enacted** | **FY 2020 Enacted** | **FY 2021 Request** | **FY 2021 Request vs FY 2020 Enacted** |
| Research | 209,705 | 202,575 | 197,880 | -4,695 |
| Facility Operations | 357,521 | 399,380 | 405,169 | +5,789 |
| Projects | | | | |
| Major Items of Equipment | 23,760 | 21,620 | 8,240 | -13,380 |
| Construction | 75,500 | 65,100 | 19,800 | -45,300 |
| Total, Projects | 99,260 | 86,720 | 28,040 | -58,680 |
| Other | 23,514 | 24,325 | 22,238 | -2,087 |
| **Total, Nuclear Physics** | **690,000** | **713,000** | **653,327** | **-59,673** |

**Nuclear Physics**
**Scientific User Facility Operations**

The treatment of user facilities is distinguished between two types: TYPE A facilities that offer users resources dependent on a single, large-scale machine; TYPE B facilities that offer users a suite of resources that is not dependent on a single, large-scale machine.

**Definitions for TYPE A facilities:**
Achieved Operating Hours – The amount of time (in hours) the facility was available for users.

Planned Operating Hours –
- For Past Fiscal Year (PY), the amount of time (in hours) the facility was planned to be available for users.
- For Current Fiscal Year (CY), the amount of time (in hours) the facility is planned to be available for users.
- For the Budget Fiscal Year (BY), based on the proposed Budget Request the amount of time (in hours) the facility is anticipated to be available for users.

Optimal Hours – The amount of time (in hours) a facility would be available to satisfy the needs of the user community if unconstrained by funding levels.

Percent of Optimal Hours – An indication of utilization effectiveness in the context of available funding; it is not a direct indication of scientific or facility productivity.
- For BY and CY, Planned Operating Hours divided by Optimal Hours expressed as a percentage.
- For PY, Achieved Operating Hours divided by Optimal Hours.

Unscheduled Downtime Hours - The amount of time (in hours) the facility was unavailable to users due to unscheduled events. NOTE: For type "A" facilities, zero Unscheduled Downtime Hours indicates Achieved Operating Hours equals Planned Operating Hours.

(dollars in thousands)

| | FY 2019 Enacted | FY 2019 Current | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|---|---|
| **TYPE A FACILITIES** | | | | | |
| **CEBAF (TJNAF)**[a] | **$128,067** | **$131,269** | **$133,907** | **$128,409** | **-$5,498** |
| Number of users | 1,690 | 1,690 | 1,690 | 1,560 | -130 |
| Achieved operating hours | N/A | 4,362 | N/A | N/A | N/A |
| Planned operating hours | 4,080 | 4,080 | 2,560 | 3,010 | +450 |
| Optimal hours | 4,250 | 4,250 | 2,560 | 4,430 | +1,870 |
| Percent optimal hours | 96.0% | 102.6% | 100.0% | 67.9% | -32.1% |
| Unscheduled downtime hours | N/A | — | N/A | N/A | N/A |

[a] During FY 2017, the planned operating hours and optimal hours include 330 hours of operations (commissioning) that are supported from 12 GeV CEBAF Upgrade OPC funding, or pre-ops, that are part of the project TPC. FY 2018 is the first year of operations after project completion; optimal hours increase in FY 2018 and FY 2019 as operational experience is gained.

| | (dollars in thousands) | | | | |
|---|---|---|---|---|---|
| | FY 2019 Enacted | FY 2019 Current | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
| **RHIC (BNL)** | **$199,705** | **$198,833** | **$203,323** | **$201,044** | **-2,279** |
| Number of users | 990 | 990 | 990 | 990 | — |
| Achieved operating hours | N/A | 3,798 | N/A | N/A | N/A |
| Planned operating hours | 3,290 | 3,290 | 3,260 | 2,580 | -680 |
| Optimal hours | 3,700 | 3,700 | 3,700 | 2,580 | -1,120 |
| Percent optimal hours[a] | 88.9% | 102.6% | 88.1% | 100.0% | +11.9% |
| Unscheduled downtime hours | N/A | — | N/A | N/A | N/A |
| **ATLAS (ANL)** | **$25,947** | **$26,638** | **$25,846** | **$23,077** | **-$2,769** |
| Number of users | 310 | 310 | 340 | 300 | -40 |
| Achieved operating hours | N/A | 6,775 | N/A | N/A | N/A |
| Planned operating hours | 6,400 | 6,400 | 5,950 | 2,980 | -2,970 |
| Optimal hours | 6,800 | 6,800 | 6,400 | 6,800 | +400 |
| Percent optimal hours | 94.1% | 99.6% | 93.0% | 43.8% | -49.1% |
| Unscheduled downtime hours | N/A | — | N/A | N/A | N/A |
| **FRIB (MSU)** | **$3,950** | **$3,950** | **$28,500** | **$25,620** | **-$2,880** |
| Number of users | N/A | N/A | N/A | N/A | N/A |
| Achieved operating hours | N/A | N/A | N/A | N/A | N/A |
| Planned operating hours | N/A | N/A | N/A | N/A | N/A |
| Optimal hours | N/A | N/A | N/A | N/A | N/A |
| Percent optimal hours | N/A | N/A | N/A | N/A | N/A |
| Unscheduled downtime hours | N/A | N/A | N/A | N/A | N/A |

[a] RHIC was able to exceed planned optimal hours in FY 2018 due to unanticipated high reliabilities associated with the low energy beam scans.

| | (dollars in thousands) | | | | |
|---|---|---|---|---|---|
| | FY 2019 Enacted | FY 2019 Current | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
| **Total Facilities** | **$357,669** | **$360,690** | **$391,576** | **$378,150** | **-$13,426** |
| Number of users | 2,990 | 2,990 | 3,020 | 2,850 | -170 |
| Achieved operating hours | N/A | 14,935 | N/A | — | — |
| Planned operating hours | 13,770 | 13,770 | 11,770 | 8,570 | -3,200 |
| Optimal hours | 14,750 | 14,750 | 12,660 | 13,060 | -400 |
| Percent optimal hours[a] | 91.9% | 102.4% | 92.8% | 84.6% | -8.2% |
| Unscheduled downtime hours | N/A | — | N/A | N/A | N/A |

**Nuclear Physics**
**Scientific Employment**

| | FY 2019 Enacted | FY 2020 Enacted | FY 2021 Request | FY 2021 Request vs FY 2020 Enacted |
|---|---|---|---|---|
| Number of permanent Ph.D.'s (FTEs) | 830 | 839 | 821 | -18 |
| Number of postdoctoral associates (FTEs) | 350 | 326 | 319 | -7 |
| Number of graduate students (FTEs) | 550 | 530 | 481 | -49 |
| Other scientific employment (FTEs)[b] | 1,060 | 1,030 | 964 | -66 |

[a] For total facilities only, this is a "funding weighted" calculation FOR ONLY TYPE A facilities: $\frac{\sum_1^n[(\%OH \text{ for facility } n) \times (\text{funding for facility } n \text{ operations})]}{\text{Total funding for all facility operations}}$

[b] Includes technicians, engineers, computer professionals and other support staff.

**20-SC-51, United States Stable Isotope Production and Research Center (U.S. SIPRC)**
**Oak Ridge National Laboratory, Oak Ridge, Tennessee**
**Project is for Design and Construction**

## 1. Summary, Significant Changes, and Schedule and Cost History

**Summary**

The FY 2021 request for the United States Stable Isotope Production and Research Center (U.S. SIPRC) is $12,000,000 of TEC funding. The current Total Project Cost (TPC) point estimate is $229,000,000 with an updated preliminary TPC range of $175,000,000 to $298,000,000 in preparation for CD-1 consideration.

**Significant Changes**

This project data sheet (PDS) is an update of the FY 2020 PDS; the project is not a new start in FY 2021. The most recent DOE O 413.3B approved Critical Decision (CD) is CD-0, Approve Mission Need, which was approved on January 4, 2019. FY 2021 funding will continue support for project engineering and design activities and planned long lead procurements, such as site preparations and materials for known designs of technologies developed under previous projects. The prior projects referenced include the completed Enriched Stable Isotope Production Prototype (ESIPP) and the ongoing Stable Isotope Production Facility (SIPF) Major Item of Equipment.

A Federal Project Director (FPD) with certification level 3 has been assigned to the U.S. SIPRC.

**Critical Milestone History**

| Fiscal Year | CD-0 | Conceptual Design Complete | CD-1 | CD-2 | Final Design Complete | CD-3 | D&D Complete | CD-4 |
|---|---|---|---|---|---|---|---|---|
| FY 2020[a] | 1/04/19 | 2Q FY 2020 | 2Q FY 2020 | 2Q FY 2021 | TBD | 2Q FY 2022 | N/A | 4Q FY 2026 |
| FY 2021[b] | 1/04/19 | 4Q FY 2020 | 4Q FY 2020 | 3Q FY 2022 | 2Q FY 2022 | 3Q FY 2022 | N/A | 4Q FY 2027 |

**CD-0** – Approve Mission Need for a construction project with a conceptual scope and cost range
**Conceptual Design Complete** – Actual date the conceptual design was completed (if applicable)
**CD-1** – Approve Alternative Selection and Cost Range
**CD-2** – Approve Performance Baseline
**Final Design Complete** – Estimated/Actual date the project design will be/was complete (d)
**CD-3** – Approve Start of Construction
**D&D Complete** – Completion of D&D work
**CD-4** – Approve Start of Operations or Project Closeout

| Fiscal Year | Performance Baseline Validation | CD-3A |
|---|---|---|
| FY 2021 | 3Q FY2022 | 4Q FY 2020 |

**CD-3A** – Approve Long-Lead Procurements, (Site preparations, EMIS components)

[a] Dates presented in FY 2020 are pre-CD-1 and are notional.
[b] The project does not have CD-1 or CD-2 approval. The schedules are only estimates and are consistent with the high end of the schedule ranges.

**Project Cost History**

This project is at CD-0 with an updated point estimate of $229,000,000 and Total Project Cost (TPC) range of $175,000,000 to $298,000,000. The point estimate increased as the footprint of the building increased to accommodate the evolving conceptual design of the gas centrifuges. The table below reflects the upper cost of the TPC range as there is not yet a baseline. No construction, excluding for approved long lead procurement, will be performed until the project performance baseline has been validated and CD-3 has been approved.

(dollars in thousands)

| Fiscal Year | TEC, Design | TEC, Construction | TEC, Total | OPC, Except D&D | OPC, D&D | OPC, Total | TPC |
|---|---|---|---|---|---|---|---|
| FY 2020 | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| FY 2021[a] | 14,000 | 274,000 | 288,000 | 10,000 | N/A | 10,000 | 298,000 |

## 2. Project Scope and Justification

**Scope**

The scope of this project includes design and construction of a building and associated instrumentation for enriching isotopes. Electromagnetic isotope separator systems and gas centrifuge cascades will be designed and implemented in this new single facility to promote operational, cost and security effectiveness, with space for future growth. The planned facility will include adequate space for test stands and prototype development and will be a purely technical facility (i.e., minimal office and staff amenities), and located on the ORNL main campus. Gas centrifuges and electromagnetic separators are leveraged by existing designs developed from prior projects and R&D supported by DOE IP. The laboratory is considering the optimal number of each type of technology as part of the alternatives analysis for Critical Decision-1 (CD-1).

**Justification**

U.S. SIPRC is critical to the DOE Isotope Program within SC's Office of Nuclear Physics (NP). The facility will expand the stable isotope production capability to address multiple production capabilities to meet the demand of the nation, while also mitigating our Nation's dependencies on foreign suppliers for critical isotopes. The current capacity within the United States is insufficient to meet the Nation's growing demands, and is spread out geographically at ORNL in smaller buildings, which increases operating complexity, operating costs, and complicates security protection strategies. U.S. SIPRC will provide an adequately sized building and consolidated approach to address our Nation's isotope needs in a more economical and operational efficient manner.

U.S. SIPRC will expand current production capabilities for enriched stable isotopes and provide a new building that will facilitate efficient operations and provide space, not only for all of the current needs, but will also accommodate the projected large-scale expansion of production systems.

The project is being conducted in accordance with the project management requirements in DOE O 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, and all appropriate project management requirements will be met.

[a] The project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.

Key Performance Parameters (KPPs)[a]

Preliminary Key Performance Parameters (KPPs) are defined at CD-1 and may change as the project continues towards CD-2. At CD-2 approval, the KPPs will be baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

| Performance Measure | Threshold | Objective |
|---|---|---|
| TBD | TBD | TBD |

**3. Funding Schedule**

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Total Estimated Cost (TEC)[b]** | | | |
| PED | | | |
| FY 2020 | 12,000 | 12,000 | 2,700 |
| FY 2021 | 2,000 | 2,000 | 11,300 |
| Outyears | — | — | — |
| Total, PED | 14,000 | 14,000 | 14,000 |
| Construction | | | |
| FY 2020 | — | — | — |
| FY 2021 | 10,000 | 10,000 | 8,000 |
| Outyears | N/A | N/A | 266,000 |
| Total, Construction | N/A | N/A | 274,000 |
| Total Estimated Cost (TEC) | | | |
| FY 2020 | 12,000 | 12,000 | 2,700 |
| FY 2021 | 12,000[c] | 12,000 | 19,300 |
| Outyears | 264,000 | 264,000 | 266,000 |
| **Total, TEC** | **288,000** | **288,000** | **288,000** |
| **Other Project Cost (OPC)** | | | |
| OPC except D&D | | | |
| FY 2019 | 500 | 500 | 171 |
| FY 2020 | 2,100 | 2,100 | 2,429 |
| FY 2021 | — | — | — |
| Outyears | 7,400 | 7,400 | 7,400 |
| **Total, OPC** | **10,000** | **10,000** | **10,000** |

[a] The project does not have CD-1 approval. Preliminary KPPs are defined at CD-1. CD-1 is planned for 2020.

[b] The project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.

[c] Includes an estimated $10,000,000 for long lead procurements associated with site preparations and EMIS components.

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Total Project Cost (TPC)** | | | |
| FY 2019 | 500 | 500 | 171 |
| FY 2020 | 14,100 | 14,100 | 5,129 |
| FY 2021 | 12,000 | 12,000 | 19,300 |
| Outyears | 271,400 | 271,400 | 273,400 |
| **Total, TPC[a]** | **298,000** | **298,000** | **298,000** |

**4. Details of Project Cost Estimate**

(dollars in thousands)

| | Current Total Estimate | Previous Total Estimate | Original Validated Baseline |
|---|---|---|---|
| **Total Estimated Cost (TEC)** | | | |
| Design | | | |
| Design | 12,000 | 11,700[b] | N/A |
| Contingency | 2,000 | 2,000 | N/A |
| Total, Design | 14,000 | 13,700 | N/A |
| Construction | | | |
| Construction | 210,000 | TBD | N/A |
| Contingency | 64,000 | TBD | N/A |
| Total, Construction | 274,000 | TBD | N/A |
| **Total, TEC** | **288,000** | **13,700** | **N/A** |
| *Contingency, TEC* | *66,000* | *2,000* | *N/A* |
| **Other Project Cost (OPC)** | | | |
| OPC except D&D | | | |
| R&D | — | TBD | N/A |
| Conceptual Design | 2,600 | 500 | N/A |
| Start-up | 5,000 | TBD | N/A |
| Contingency | 2,400 | TBD | N/A |
| **Total, OPC** | **10,000** | **TBD** | **N/A** |
| *Contingency, OPC* | *2,400* | *TBD* | *N/A* |
| **Total Project Cost[a]** | **298,000** | **TBD** | **N/A** |
| ***Total, Contingency (TEC+OPC)*** | ***68,400*** | ***TBD*** | ***N/A*** |

[a] The project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.

[b] The "Previous Total Estimate" of $5,000 for Design in the FY 2020 submitted PDS represented only the value requested in that year, not the total estimate.

## 5. Schedule of Appropriations Requests[a]

(dollars in thousands)

| Request Year | Type | Prior Years | FY 2019 | FY 2020 | FY 2021 | Outyears | Total |
|---|---|---|---|---|---|---|---|
| FY 2020 | TEC | — | — | 5,000 | — | — | TBD |
| | OPC | — | 500 | — | — | — | TBD |
| | TPC | — | 500 | — | — | — | TBD |
| FY 2021 | TEC | — | — | 12,000 | 12,000 | 264,000 | 288,000 |
| | OPC | — | 500 | 2,100 | — | 7,400 | 10,000 |
| | TPC | — | 500 | 14,100 | 12,000 | 271,400 | 298,000[a] |

## 6. Related Operations and Maintenance Funding Requirements

| | |
|---|---|
| Start of Operation or Beneficial Occupancy[a] | 4Q FY 2027 |
| Expected Useful Life | — |
| Expected Future Start of D&D of this capital asset | — |

Related Funding Requirements
(dollars in thousands)

| | Annual Costs | | Life Cycle Costs | |
|---|---|---|---|---|
| | Previous Total Estimate | Current Total Estimate | Previous Total Estimate | Current Total Estimate |
| Operations | N/A | — | N/A | — |
| Utilities | N/A | — | N/A | — |
| Maintenance and Repair | N/A | — | N/A | — |
| Total, Operations and Maintenance | N/A | — | N/A | — |

## 7. D&D Information

| | Square Feet |
|---|---|
| Area of new construction | 43,000 |
| Area of existing facility(ies) being replaced | N/A |
| Area of any additional D&D space to meet the “one-for-one” requirement | N/A |

The new area being constructed in this project is not replacing existing facilities. Any existing space that is freed up from consolidating activities into SIPRC will likely be repurposed.

[a] This project does not yet have CD-1 approval. CD-1 approval is scheduled for FY 2020. Section 6 will be filled out in the next budget cycle, after CD-1 approval.

## 8. Acquisition Approach

The acquisition approach will be approved with CD-1 approval, anticipated to be in FY 2020. ORNL will manage all acquisitions with appropriate DOE oversight. DOE and ORNL will monitor cost, schedule, and technical performance using an earned-value process consistent with DOE O 413.3B, *Program and Project Management for the Acquisition of Capital Assets*. ORNL will construct the building and production machines, including the acquisition of specialty equipment.

**20-SC-52, Electron-Ion Collider (EIC)**
**Brookhaven National Laboratory**
**Project is for Design**

## 1. Summary, Significant Changes, and Schedule and Cost History

**Summary**

The FY 2021 Request for the Electron-Ion Collider is $2,500,000 in Total Project Cost (TPC) funding. DOE O 413.3B Critical Decision (CD)-0, Approve Mission Need, was received on December 19, 2019. The preliminary TPC at CD-0 approval was $1.6 billion to $4.2 billion. On January 9, 2020, DOE selected Brookhaven National Laboratory as the location for the EIC. This selection establishes a new cost range of $1.6 billion to $2.6 billion for the EIC.

**Significant Changes**

The EIC was initiated in the FY 2020 Enacted Appropriation. This initial construction project data sheet for FY 2021 funding does not represent a new start for the budget year.

Of the $2,500,000 TPC funding requested in FY 2021, $1,500,000 will continue to support the conceptual design and research and development efforts funded under Other Project Costs. The remaining $1,000,000 of Total Estimated Costs will support engineering and design efforts.

A Federal Project Director (FPD) will be assigned by CD-1.

**Critical Milestone History**

| Fiscal Year | CD-0 | Conceptual Design Complete | CD-1 | CD-2 | Final Design Complete | CD-3 | D&D Complete | CD-4 |
|---|---|---|---|---|---|---|---|---|
| FY 2021[a] | 12/19/19 | 4Q FY 2021 | 4Q FY 2021 | 4Q FY 2023 | 4Q FY 2024 | 4Q FY 2024 | N/A | 4Q FY 2032 |

**CD-0** – Approve Mission Need for a construction project with a conceptual scope and cost range
**Conceptual Design Complete** – Actual date the conceptual design was completed (if applicable)
**CD-1** – Approve Alternative Selection and Cost Range
**CD-2** – Approve Performance Baseline
**Final Design Complete** – Estimated/Actual date the project design will be/was complete (d)
**CD-3** – Approve Start of Construction
**D&D Complete** – Completion of D&D work
**CD-4** – Approve Start of Operations or Project Closeout

| Fiscal Year | Performance Baseline Validation | CD-3A | CD-3B |
|---|---|---|---|
| FY 2021 | 4Q 2023 | TBD | N/A |

**CD-3A** – Approve Long-Lead Procurements, Original Scope
**CD-3B** – Approve Long-Lead Procurements, Revised Scope

[a] The project is pre-CD-2; therefore, funding and schedule estimates are preliminary.

**Project Cost History**

(dollars in thousands)

| Fiscal Year | TEC, Design | TEC, Construction | TEC, Total | OPC, Except D&D | OPC, D&D | OPC, Total | TPC |
|---|---|---|---|---|---|---|---|
| FY 2020 | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| FY 2021[a] | 340,000 | 2,010,000 | 2,350,000 | 250,000 | N/A | 250,000 | 2,600,000 |

The preliminary TPC at CD-0 approval was $1.6 billion to $4.2 billion. On January 9, 2020, DOE selected Brookhaven National Laboratory as the location for the EIC. This selection establishes a new cost range of $1.6 billion to $2.6 billion for the EIC. The project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.

**2. Project Scope and Justification**

**Scope**

The scope of this project includes the key EIC machine parameters required to address the scientific agenda listed in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plans (LRP). These parameters include a high degree of beam polarization (approximately 70 percent) for electrons and light ions, availability of ion beams from deuterons to the heaviest stable nuclei, variable center of mass energies about 20–100 GeV, upgradable to about 140 GeV (e-p), high collision luminosity about $10^{33\text{-}34}$ $cm^{-2}s^{-1}$, and possibly more than one interaction region. The scope will also include the ancillary facilities, such as power and cryoplants, necessary to support the operations of the EIC.

**Justification**

The last three NSAC LRP reports have supported the EIC with recommendations ranging from investing in accelerator research and development (R&D) in the 2002 NSAC LRP, to reducing technical risks in the 2007 NSAC LRP, to the actual construction of a U.S.-based EIC in the 2015 NSAC LRP. Specifically, the 2015 NSAC LRP for Nuclear Science recommended a high-energy, high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. Consistent with that vision, in 2016 NP commissioned a National Academies of Sciences (NAS) study by an independent panel of external experts to assess the uniqueness and scientific merit of such a facility. The report, released in July 2018, strongly supports the scientific case for building a U.S.-based EIC, documenting that an EIC will advance the understanding of the origins of nucleon mass, the origin of the spin properties of nucleons, and the behavior of gluons.

The project is being conducted in accordance with the project management requirements in DOE O 413.3B, *Program and Project Management for the Acquisition of Capital Assets.*

Key Performance Parameters (KPPs)[b]

Preliminary Key Performance Parameters (IPPs) are defined at CD-1 and may change as the project continues towards CD-2. At CD-2 approval, the KPPs are baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

| Performance Measure | Threshold | Objective |
|---|---|---|
| TBD | TBD | TBD |

[a] The project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.

[b] The project does not have CD-1 approval. Preliminary KPPs are defined at CD-1. CD-1 is planned for 2021.

### 3. Financial Schedule[a]

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Total Estimated Cost (TEC)** | | | |
| Design | | | |
| FY 2020 | 1,000 | 1,000 | — |
| FY 2021 | 1,000 | 1,000 | 1,750 |
| Outyears | 338,000 | 338,000 | 338,250 |
| Total, Design[b] | 340,000 | 340,000 | 340,000 |
| Construction | | | |
| FY 2020 | — | — | — |
| FY 2021 | — | — | — |
| Outyears | 2,010,000 | 2,010,000 | 2,010,000 |
| Total, Construction[b] | 2,010,000 | 2,010,000 | 2,010,000 |
| Total Estimated Costs (TEC) | | | |
| FY 2020 | 1,000 | 1,000 | — |
| FY 2021 | 1,000 | 1,000 | 1,750 |
| Outyears | 2,348,000 | 2,348,000 | 2,348,250 |
| **Total, TEC[b]** | **2,350,000** | **2,350,000** | **2,350,000** |
| **Other Project Costs (OPC)** | | | |
| FY 2020 | 10,000 | 10,000 | 9,500 |
| FY 2021 | 1,500 | 1,500 | 2,000 |
| Outyears | 238,500 | 238,500 | 238,500 |
| **Total, OPC[b]** | **250,000** | **250,000** | **250,000** |
| **Total Project Costs (TPC)** | | | |
| FY 2020 | 11,000 | 11,000 | 9,500 |
| FY 2021 | 2,500 | 2,500 | 3,750 |
| Outyears | 2,586,500 | 2,586,500 | 2,586,750 |
| **Total, TPC[b]** | **2,600,000** | **2,600,000** | **2,600,000** |

[a] This project is at the CD-0 stage. Dollars presented are through current budget request only. An estimated financial schedule will be provided in the FY 2022 President's Request.
[b] The project does not have CD-1 or CD-2 approval. The schedules are costs are only estimates and are consistent with the high end of the schedule and cost ranges.

## 4. Details of Project Cost Estimate[a]

(dollars in thousands)

| | Current Total Estimate | Previous Total Estimate | Original Validated Baseline |
|---|---|---|---|
| **Total Estimated Cost (TEC)** | | | |
| Design | | | |
| Design | 250,000 | N/A | N/A |
| Contingency | 90,000 | N/A | N/A |
| Total, Design | 340,000 | N/A | N/A |
| Construction | | | |
| Construction | 1,490,000 | N/A | N/A |
| Contingency | 520,000 | N/A | N/A |
| Total, Construction | 2,010,000 | N/A | N/A |
| **Total, TEC** | **2,350,000** | **N/A** | **N/A** |
| *Contingency, TEC* | 610,000 | N/A | N/A |
| **Other Project Cost (OPC)** | | | |
| OPC except D&D | | | |
| R&D | 30.000 | N/A | — |
| Conceptual Design | 40,000 | N/A | N/A |
| Other OPC Costs | 115,000 | N/A | N/A |
| Contingency | 65,000 | N/A | N/A |
| **Total, OPC** | **250,000** | **N/A** | **N/A** |
| *Contingency, OPC* | 65,000 | N/A | — |
| **Total Project Cost[a]** | **2,600,000** | **TBD** | **TBD** |
| ***Total, Contingency (TEC+OPC)*** | **675,000** | **TBD** | **TBD** |

## 5. Schedule of Appropriations Requests[b]

(dollars in thousands)

| Request Year | Type | Prior Years | FY 2019 | FY 2020 | FY 2021 | Outyears | Total |
|---|---|---|---|---|---|---|---|
| FY 2021 | TEC | — | — | 1,000 | 1,000 | — | — |
| | OPC | — | — | 10,000 | 1,500 | — | — |
| | TPC | — | — | 11,000 | 2,500 | — | — |

[a] This project does not have CD-1 or CD-2 approval. The schedules and costs are only estimates and are consistent with the high end of the schedule and cost ranges.
[b] This project is at the CD-0 stage. Dollars presented are through current budget request only. Estimated values for the schedule of appropriation requests will be provided in the FY 2022 President's Request.

## 6. Related Operations and Maintenance Funding Requirements

| | |
|---|---|
| Start of Operation or Beneficial Occupancy | 4Q FY 2032 |
| Expected Useful Life | TBD |
| Expected Future Start of D&D of this capital asset | TBD |

Related Funding Requirements
(dollars in thousands)

| | Annual Costs | | Life Cycle Costs | |
|---|---|---|---|---|
| | Previous Total Estimate | Current Total Estimate | Previous Total Estimate | Current Total Estimate |
| Operations and Maintenance | TBD | TBD | TBD | TBD |

## 7. D&D Information

The new area being constructed in this project is not replacing existing facilities.

| | Square Feet |
|---|---|
| New area being constructed by this project at Site TBD ........ | TBD |
| Area of D&D in this project at Site TBD ........ | TBD |
| Area at Site TBD to be transferred, sold, and/or D&D outside the project, including area previously "banked" ........ | TBD |
| Area of D&D in this project at other sites ........ | TBD |
| Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked" ........ | TBD |
| Total area eliminated ........ | TBD |

## 8. Acquisition Approach

The acquisition approach will be approved with CD-1, anticipated to be in FY 2020. Brookhaven National Laboratory has been selected as the site. It will manage all acquisitions with appropriate Department of Energy oversight, and monitor cost, schedule, and technical performance with DOE using an earned-value process consistent with DOE O 413.3B, *Program and Project Management for the Acquisition of Capital Assets*.

**14-SC-50, Facility for Rare Isotope Beams (FRIB)**
**Michigan State University (MSU), East Lansing, MI**
**Project is for a Cooperative Agreement**

## 1. Summary, Significant Changes, and Schedule and Cost History


**Summary**

The FY 2021 Request for the Facility for Rare Isotope Beams (FRIB) project is $5,300,000. The Total Project Cost (TPC) at CD-3B approval is $635,500,000, with a scheduled CD-4 by 3Q FY 2022. Michigan State University (MSU) is providing an additional cost share of $94,500,000, bringing the total project cost to $730,000,000.


**Significant Changes**

This PDS is an update of the FY 2020 PDS and does not include a new start for FY 2021. The most recent Critical Decision (CD) for the FRIB project is CD-3B, Approve Start of Technical Construction of the Accelerator and Experimental Systems, which was approved on August 26, 2014.

Start of civil construction officially began in March 2014, and technical construction began in August 2014. Since the start of the civil and technical construction, multiple independent project assessments, the most recent being in May 2019, have determined the project is proceeding on track and within the established project baseline. There are no changes in the project's scope since the establishment of the project's baseline. The Request will complete installation and testing of cryomodules and experimental systems, as well as commissioning efforts associated with technical components as they are completed.

FRIB is funded through a cooperative agreement financial assistance award with MSU per 2 CFR 200, and the project is required by this agreement to follow the principles of the DOE Order 413.3B. Funding tables contained in sections 3 and 4 of this PDS differ slightly from a traditional PDS for a federal capital asset construction project for how the baseline is presented in that they include the MSU cost share. The table in section 5, Schedule of Appropriations Requests, displays only DOE funding.

A Federal Project Director with certification Level 4 has been assigned to this project and approves this PDS.

**Critical Milestone History**

| Fiscal Year | CD-0 | Conceptual Design Complete | CD-1 | CD-2 | Final Design Complete | CD-3A | CD-3B | D&D Complete | CD-4 |
|---|---|---|---|---|---|---|---|---|---|
| FY 2011 | 2/09/04 | | 4Q FY 2010 | TBD | TBD | TBD | TBD | N/A | FY 2017-2019 |
| FY 2012 | 2/09/04 | | 9/01/10 | 4Q FY 2012 | TBD | TBD | TBD | N/A | FY 2018-2020 |
| FY 2013 | 2/09/04 | | 9/01/10 | TBD | TBD | TBD | TBD | N/A | TBD |
| FY 2014 | 2/09/04 | | 9/01/10 | 3Q FY 2013 | TBD | 3Q FY 2013 | TBD | N/A | TBD |
| FY 2015 | 2/09/04 | | 9/01/10 | 8/01/13 | 4Q FY 2014 | 8/01/13 | 4Q FY 2014 | N/A | 3Q FY 2022 |

| Fiscal Year | CD-0 | Conceptual Design Complete | CD-1 | CD-2 | Final Design Complete | CD-3A | CD-3B | D&D Complete | CD-4 |
|---|---|---|---|---|---|---|---|---|---|
| FY 2016 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14[a] | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |
| FY 2017 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14[a] | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |
| FY 2018 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14 | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |
| FY 2019 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14 | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |
| FY 2020 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14 | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |
| FY 2021 | 2/09/04 | 9/01/10 | 9/01/10 | 8/01/13 | 8/26/14 | 8/01/13 | 8/26/14 | N/A | 3Q FY 2022 |

**CD-0** – Approve Mission Need for a construction project with a conceptual scope and cost range
**Conceptual Design Complete** – Actual date the conceptual design was completed (if applicable)
**CD-1** – Approve Alternative Selection and Cost Range
**CD-2** – Approve Performance Baseline
**Final Design Complete** – Estimated/Actual date the project design will be/was complete (d)
**CD-3** – Approve Start of Construction
**CD-3A** – Approve Long-Lead Procurements, Original Scope
**CD-3B** – Approve Long-Lead Procurements, Revised Scope
**D&D Complete** – Completion of D&D work
**CD-4** – Approve Start of Operations or Project Closeout

**Project Cost History** [b]

(dollars in thousands)

| Fiscal Year | Design/ Construction | R&D/ Conceptual Design/NEPA | Pre-Operations | Total TPC | Less MSU Cost Share | DOE TPC |
|---|---|---|---|---|---|---|
| FY 2015 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2016 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2017 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2018 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2019 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2020 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |
| FY 2021 | 655,700 | 24,600 | 49,700 | 730,000 | -94,500 | 635,500 |

## 2. Project Scope and Justification

### Scope

FRIB scope includes the design, construction, fabrication, assembly, testing, and commissioning of the civil and technical scope that will enable high intensity primary beams of stable isotopes to be accelerated up to a minimum energy of 200 MeV per nucleon by a superconducting linear accelerator (linac) capable of delivering 400 kW of beam power at full energy. The scope also includes the capability for secondary beams of rare isotopes to be produced “in-flight” and separated from

[a] This date represents when the design was substantially complete to allow the start of technical construction (CD-3B). A limited amount of design effort continued through 4Q FY 2017.

[b] Because this project is funded with operating dollars through a financial assistance award, its baseline is categorized through a work breakdown structure (WBS), which is slightly different from typical federal capital assets. Note that the project’s WBS totals $730,000,000 including MSU’s cost share. The WBS scope is not pre-assigned to DOE or MSU funds.

unwanted fragments by magnetic analysis. In support of these capabilities, the civil construction portion includes a structure of approximately 220,000 square feet that will house the linac tunnel, target high bay area, linac support area, and cryoplant area. The technical scope includes a 2K/4.5K cryogenics plant, linac front end, cryomodules, and experimental systems.

**Justification**

The science that underlies the FRIB mission is a core competency of nuclear physics: understanding how protons and neutrons combine to form various nuclear species; understanding how long chains of different nuclear species survive; and understanding how one nuclear species decays into another and what is emitted when that happens. Forefront knowledge and capability in this competency is essential, both for U.S. leadership in this scientific discipline and to provide the knowledge and workforce needed for numerous activities and applications relevant to national security and economic competitiveness.

FRIB will provide intense beams of rare isotopes for a wide variety of studies in nuclear structure, nuclear astrophysics, and other topics in nuclear physics. This facility will enable the study of the origin of the elements and the evolution of the cosmos, and offers an opportunity for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a more broadly applicable theory of nuclei will emerge. The facility will offer new glimpses into the origin of the elements, leading to a better understanding of key issues by creating exotic nuclei that, until now, have existed only in nature's most spectacular explosion, the supernova.

FRIB is optimized to produce large quantities of a wide variety of rare isotopes by breaking stable nuclei into these rare isotopes. High intensity primary beams of stable isotopes are produced in Electron Cyclotron Resonator ion sources and accelerated up to a minimum energy of 200 MeV per nucleon by a superconducting linear accelerator capable of delivering 400 kW of beam power at full energy. Secondary beams of rare isotopes are produced "in-flight" and separated from unwanted fragments by magnetic analysis. These rare isotope beams are delivered to experimental areas or stopped in a suite of ion-stopping stations where they can be extracted and used for experiments at low energy, or reaccelerated for astrophysical experiments or for nuclear structure experiments. The project includes the necessary infrastructure and support facilities for operations and the 1,000-person user community.

As contractually required under the financial assistance award agreement, FRIB is being constructed in accordance with the project management principles in DOE Order 413.3B, Program and Project Management for the Acquisition of Capital Assets, and all appropriate project management requirements have been met.

Key Performance Parameters (KPPs)

The Key Performance Parameters (KPPs) are preliminary and may change as the project continues towards CD-2. At CD-2 approval, the KPPs will be baselined. The Threshold KPPs represent the minimum acceptable performance that the project must achieve. The Objective KPPs represent the desired project performance. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

| System | Parameter | Performance Criteria |
|---|---|---|
| Accelerator System | Accelerate heavy-ion beam | Measure FRIB driver linac Argon-36 beam with energy larger than 200 MeV per nucleon and a beam current larger than 20 pico nano amps (pnA) |
| Experimental Systems | Produce a fast rare isotope beam of Selenium-84 | Detect and identify Selenium-84 isotopes in FRIB fragment separator focal plane |
| | Stop a fast rare isotope beam in gas and reaccelerate a rare isotope beam | Measure reaccelerated rare isotope beam energy larger than 3 MeV per nucleon |

| System | Parameter | Performance Criteria |
|---|---|---|
| Conventional Facilities | Linac tunnel | Beneficial occupancy of subterranean tunnel structure of approximately 500 feet path length (minimum) to house FRIB driver linear accelerator |
| | Cryogenic helium liquefier plant—building and equipment | Beneficial occupancy of the cryogenic helium liquefier plant building and installation of the helium liquefier plant complete |
| | Target area | Beneficial occupancy of target area and one beam line installed and ready for commissioning |

### 3. Financial Schedule[a]

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs[b] |
|---|---|---|---|
| **DOE Total Project Cost (TPC)** | | | |
| FY 2009 | 7,000 | 7,000 | 4,164 |
| FY 2010 | 12,000 | 12,000 | 13,283 |
| FY 2011 | 10,000 | 10,000 | 11,553 |
| FY 2012 | 22,000 | 22,000 | 18,919 |
| FY 2013 | 22,000 | 22,000 | 20,677 |
| FY 2014[c] | 55,000 | 55,000 | 48,369 |
| FY 2015 | 90,000 | 90,000 | 79,266 |
| FY 2016 | 100,000 | 100,000 | 121,769 |
| FY 2017 | 100,000 | 100,000 | 100,000 |
| FY 2018 | 97,200 | 97,200 | 84,124 |
| FY 2019 | 75,000 | 75,000 | 38,344 |
| FY 2020 | 40,000 | 40,000 | 42,000 |
| FY 2021 | 5,300 | 5,300 | 31,000 |
| Outyears | — | — | 22,032 |
| **Total, DOE TPC** | **635,500** | **635,500** | **635,500** |

[a] The funding profile represents DOE's requested portion, which is less than the current baselined TPC which includes MSU's cost share.
[b] Costs through FY 2018 reflect actual costs; costs for FY 2019 and the outyears are estimates.
[c] The first project data sheet submitted for FRIB was in the FY 2015 Congressional Budget Request. It was established as a control point in the FY 2014 appropriation. Funding for the project in FY 2013 and prior years was provided within the Low Energy subprogram.

## 4. Details of Project Cost Estimate[a]

(dollars in thousands)

| | Current Total Estimate | Previous Total Estimate | Original Validated Baseline |
|---|---|---|---|
| **DOE Total Estimated Cost (TEC)** | | | |
| Design & Construction | | | |
| Management and Support | 39,599 | 37,288 | 35,400 |
| Conventional Facilities | 208,100 | 208,100 | 165,300 |
| Accelerator Systems | 301,551 | 295,216 | 241,400 |
| Experimental Systems | 81,686 | 75,520 | 55,000 |
| Contingency (DOE Held) | 24,814 | 39,626 | 158,650 |
| Total, Design & Construction | 655,750 | 655,750 | 655,750 |
| **Other Project Cost (OPC)** | | | |
| Conceptual Design/Tech R&D/NEPA | 24,641 | 24,641 | 24,600 |
| Pre-ops/ Commissioning/Spares | 34,187 | 34,659 | 35,500 |
| Contingency (DOE Held) | 15,422 | 14,950 | 14,150 |
| Total, OPC | 74,250 | 74,250 | 74,250 |
| **Total, TPC** | **730,000** | **730,000** | **730,000** |
| *MSU Cost Share* | *94,500* | *94,500* | *94,500* |
| **Total Project Cost (DOE Share)** | **635,500** | **635,500** | **635,500** |
| ***Total, Contingency (DOE Held)*** | ***40,236*** | ***54,576*** | ***172,800*** |

## 5. Schedule of Appropriations Requests[b]

(dollars in thousands)

| Request Year | Type | Prior Years | FY 2019 | FY 2020 | FY 2021 | Outyears | Total |
|---|---|---|---|---|---|---|---|
| FY 2011 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 29,000 | — | — | — | — | 29,000 |
| FY 2012 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 59,000 | — | — | — | — | 59,000 |

[a] This section shows a breakdown of the total project cost of $730,000,000 as of 6/30/2019, which includes MSU's cost share. The scope of work is not pre-assigned to DOE or MSU funds.

[b] The funding profile represents DOE's portion of the baselined TPC to be provided through federal appropriations. TEC/OPC type efforts are managed at the DOE and MSU funding levels ($730,000,000) and not available for the DOE funding portion only.

(dollars in thousands)

| Request Year | Type | Prior Years | FY 2019 | FY 2020 | FY 2021 | Outyears | Total |
|---|---|---|---|---|---|---|---|
| FY 2013 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 73,000 | — | — | — | — | 73,000 |
| FY 2014 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 128,000 | — | — | — | — | 128,000 |
| FY 2015 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 515,200 | 75,000 | 40,000 | 5,300 | — | 635,500 |
| FY 2016 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 515,200 | 75,000 | 40,000 | 5,300 | — | 635,500 |
| FY 2017 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 515,200 | 75,000 | 40,000 | 5,300 | — | 635,500 |
| FY 2018 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 498,000 | 75,000 | 57,200 | 5,300 | — | 635,500 |
| FY 2019 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 498,000 | 75,000 | 57,200 | 5,300 | — | 635,500 |
| FY 2020 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 515,200 | 75,000 | 40,000 | 5,300 | — | 635,500 |
| FY 2021 | TEC | — | — | — | — | — | — |
| | OPC | — | — | — | — | — | — |
| | TPC | 515,200 | 75,000 | 40,000 | 5,300 | — | 635,500 |

## 6. Related Operations and Maintenance Funding Requirements

| | |
|---|---|
| Start of Operation or Beneficial Occupancy | 3Q FY 2022 |
| Expected Useful Life | 20 years |
| Expected Future Start of D&D of this capital asset | N/A[a] |

Related Funding Requirements
(dollars in thousands)

| | Annual Costs | | Life Cycle Costs | |
|---|---|---|---|---|
| | Previous Total Estimate | Current Total Estimate | Previous Total Estimate | Current Total Estimate |
| Operations[b] | 90,000 | 90,000 | 1,800,000[c] | 1,800,000 |

[a] Per the financial assistance award agreement, MSU is responsible for D&D.
[b] Utilities, maintenance, and repair costs are included within the Operations amounts.
[c] The total operations and maintenance (O&M) is estimated at an average annual cost of approximately $90,000,000 (including escalation) over 20 years.

**7. D&D Information**

The FRIB project is being constructed at MSU under a cooperative agreement financial assistance award. The one-for-one requirement, which requires the demolition of a square foot of space for every square foot added, is not applicable, since this is not a federal capital acquisition.

**8. Acquisition Approach**

FRIB project activities will be accomplished following all procurement requirements, which include using fixed-priced competitive contracts with selection based on best value. MSU has contracted for the services of an architect-engineer firm for the design of the conventional facilities. The Driver Linac and Experimental System components will be self-performed by the MSU design staff with assistance from outside vendors and from DOE national laboratories that possess specific areas of unique expertise unavailable from commercial sources. Integration of the conventional facilities with the Driver Linac and Experimental Systems will be accomplished by the MSU FRIB Project Team.