## 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 elements and the properties we observe? The mission of the Nuclear Physics (NP) program is to solve this mystery by discovering, exploring, and understanding all forms of nuclear matter—not only the familiar forms of matter we see around us, but also exotic forms that existed in the first moments after the Big Bang and that may exist today inside neutron stars. The aim is to understand why matter takes on the specific forms observed in nature and how that knowledge can benefit society in the areas of energy, commerce, medicine, and national security.

Understanding all forms of nuclear matter requires an enormous range of capabilities: from probing quarks and gluons inside protons, to searching for the largest nuclei that can exist, such as Tennessium—one of four newly discovered super-heavy nuclei. It also encompasses discovery not only from the smallest to the largest, but through time and the evolution of the universe as well. The epoch in the cosmos when quarks and gluons first combined to form protons was millionths of a second after the Big Bang. Events in the cosmos creating heavy nuclei are still occurring today. Achieving this goal therefore requires a suite of advanced tools and support for inspired scientists and engineers to use them.

Theoretical approaches to further our understanding are based largely on calculations of the interactions of quarks and gluons described by the theory of Quantum Chromodynamics (QCD). An exciting vision is the prospect of Quantum Computing—a revolutionary new paradigm for future computers capable of solving many-body QCD problems currently intractable with today's capabilities. Experimental approaches use large accelerators at national user facilities to collide particles at nearly the speed of light, producing short-lived forms of nuclear matter for investigation. Comparison of experimental observations and theoretical predictions tests the limits of our understanding of nuclear matter and suggests new directions for experimental and theoretical research. The many forms in which nuclear matter can exist requires a suite of accelerators with complementary capabilities. NP stewards operations at four such accelerator facilities.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL) recreates new forms of matter and phenomena that occurred in the extremely hot, dense environment that existed in the infant universe. The Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (TJNAF) extracts information on quarks and gluons bound inside protons and neutrons that formed shortly after the universe began to cool. The Argonne Tandem Linear Accelerator System (ATLAS) "gently" accelerates nuclei to energies typical of nuclear reactions in the cosmos to further our understanding of the ongoing synthesis of heavy elements such as e.g. gold, and platinum. Stewardship of these facilities is a priority role and goal of NP, as affirmed in the Nuclear Science Advisory Committee's (NSAC) 2015 Long Range Plan for Nuclear Science, *Reaching for the Horizon*. It also underpins achieving the broader goals set for nuclear science in the 2013 National Research Council report, *Nuclear Physics: Exploring the Heart of Matter*. CEBAF, RHIC, and ATLAS operations will become ever more reliable and efficient via the deployment of data analytics for autonomous decision making, currently under development.

To maintain U.S. leadership in nuclear physics, the Facility for Rare Isotope Beams (FRIB) and the Electron-Ion Collider (EIC) are being implemented. FRIB will uniquely afford access to eighty percent of all isotopes predicted to exist in nature, including over 1,000 never produced on earth. The answers to long-standing "grand challenge" questions such as the ultimate limits of nuclear existence and the astrophysical sites and isotopic paths to heavy element production in the cosmos will be illuminated. FRIB is now an NP scientific user facility, and begins data taking for scientific research in FY 2022. The EIC will provide unprecedented ability to x-ray the proton and discover how the mass of everyday objects is dynamically generated by the interaction of quark and gluon fields inside protons and neutrons. As noted by the National Academies, the EIC will also maintain U.S. leadership in the accelerator science and technology of colliders. These facilities provide an exciting future of discovery in Nuclear Physics.

One equally exciting NP frontier does not involve accelerators, but envisions the nucleus itself as a laboratory for observing nature's fundamental symmetries. Chief among these experiments is the search, also given high priority in the 2015 NSAC Long Range Plan, for a nuclear decay predicted to happen once in $10^{28}$ years—and only if the elusive neutrino particle turns out to be its own anti-particle. The observation of so-called neutrino-less double beta decay would result in a disruptive change in our current understanding of the elementary constituents of nuclear matter and the forces that govern them.

Additional experiments to improve the precision of the current value of the neutron lifetime and to improve limits on a possible electric dipole moment of the neutron also have the potential to change our understanding of the physical world. NP is the primary steward of the nation's fundamental nuclear physics research portfolio providing over 90 percent of the U.S. investment in this area. It also supports the National Nuclear Data Center which collects, evaluates, curates, and disseminates nuclear physics data for basic nuclear research and applied nuclear technologies. In collaboration with other SC programs, NP continues to support development of quantum sensors and quantum control techniques, as well as efforts on data analytics for autonomous decision making which can benefit nuclear physics research and NP accelerator operations. NP also stewards strategic accelerator R&D to pursue next generation electron ion source developments and advanced approaches in superconducting radio frequency (SRF) technologies. In addition, the request supports NP participation in the following SC Initiatives: Microelectronics; Integrated Computational & Data Infrastructure for cross-cutting cloud solutions to Big Data storage challenges in Nuclear Physics; and the Reaching a New Energy Sciences Workforce (RENEW) initiative.

**Highlights of the FY 2022 Request**

The FY 2022 Request for $720.0 million supports high priority efforts and capabilities in fundamental nuclear physics research; operations, maintenance and upgrades of scientific user facilities; and projects identified as essential in the 2015 NSAC Long Range Plan to maintain U.S. leadership and extend well beyond current scientific capabilities. The Request enables world-class discovery science research and R&D integration to facilitate the development of state-of-the-art applications for energy, medicine, commerce, and national security.

<u>Research</u>

- *Core Research*: Support for university and laboratory researchers to nurture critical core competencies and enable high priority theoretical and experimental activities targeting compelling scientific opportunities identified by the National Academies and NSAC at the frontiers of nuclear science: the nature of matter; the limits of nuclear existence; the search via fundamental symmetries for new physics; and R&D integration of new knowledge to benefit society in the areas of energy, commerce, medicine, and national security. Primary fundamental research thrusts include:
    - The search for a Critical Point and characterization of the quark-gluon plasma at RHIC and the LHC
    - Unraveling the mechanism underlying quark confinement at CEBAF and RHIC
    - The search for new exotic particles and anomalous violations of nature's symmetries at CEBAF
    - Probing the limits of nuclear existence; site & process for heavy element production in the cosmos at FRIB and ATLAS
    - Discovery of whether the neutrino is it own anti-particle via neutrino-less double beta decay
    - Precision measurement of the neutron's properties to search for new physics
    - Research on the strong force in many-body systems via Scientific Discovery Through Advanced Computing
    - Curation of reliable, accurate Nuclear Data for basic nuclear research and nuclear technologies

- NP Research also includes support for University Centers of Excellence which provide niche capabilities and unique "hands-on" experiences in nuclear science.
- *Quantum Information Science (QIS)*: Support continues for the SC QIS Centers established in FY 2020 along with a core research portfolio to leverage discovery opportunities in sensing, simulation, and computing at the intersections of nuclear physics and QIS, as articulated in the NSAC Report, *Nuclear Physics and Quantum Information Science.*
- *Data Analytics*: As part of the Office of Science's initiative on Artificial Intelligence/Machine Learning, support for R&D to develop pilot platforms targeting automated optimization of accelerator availability, performance and operation as well as software enabling data-analytics-driven discovery.
- *Accelerator Science and Technology Initiative*: In coordination with other SC programs, support for NP's role in strengthening U.S. supply chain robustness stewarding key technologies such as next generation electron ion source developments and advanced approaches in SRF technology that underpin U.S. leadership and competitiveness in accelerator R&D.
- *Integrated Computational & Data Infrastructure*: Seed funding to explore cross-cutting cloud solutions to Big Data storage challenges in Nuclear Physics.
- *RENEW:* The Office of Science is fully committed to advancing a diverse, equitable, and inclusive research community. This commitment is key to providing the scientific and technical expertise for U.S. leadership in nuclear physics. Toward that goal, NP will participate in the SC-wide RENEW initiative that leverages SC's world-unique national laboratories,

user facilities, and other research infrastructures to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem. This includes Minority Serving Institutions and individuals from groups historically underrepresented in STEM, but also includes students from communities with environmental justice impacts and the EPSCoR jurisdictions. The hands-on experiences gained through the RENEW initiative will open new career avenues for the participants, forming a nucleus for a future pool of talented young scientists, engineers, and technicians with the critical skills and expertise needed for the full breadth of SC research activities, including DOE national laboratory staffing.

- *Microelectronics:* In coordination with other SC programs, support for research and development of detector materials, devices, advances in front-end electronics, and integrated sensor/processor architectures.

Facility Operations

Requested funding directs efforts to operations of the NP scientific user facilities to enable world-class science:

- RHIC operates 2,310 hours (90 percent optimal). Operating hours are capped at 2,580 hours in FY 2022 to install sPHENIX.
- CEBAF operates for 3,790 hours (90 percent of optimal), enabling highest priority 12 GeV experiments.
- ATLAS operates for 5,800 hours (93 percent of optimal) to enable the most compelling experiments in nuclear structure and astrophysics.
- FRIB operations enables transition from a construction project to commissioning of a scientific user facility, including movement of critical staff from the project to the operations budget. This transition includes 2,310 hours (100% of optimal) of operation.

Projects

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

- Continuation of research and Project Engineering Design (PED) activities for the Electron-Ion Collider.
- Continuation of the Gamma-Ray Energy Tracking Array (GRETA) MIE, to enable provision of advanced, high resolution gamma ray detection capabilities for FRIB.
- Completion of the super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) MIE, to further RHIC's scientific mission by studying high rate jet production.
- Continuation of the Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) MIE to measure the parity-violating asymmetry in polarized electron-electron scattering with the 12 GeV CEBAF.
- Continuation of the Ton-scale Neutrinoless Double Beta Decay MIE to determine whether the neutrino is its own antiparticle. Funding supports the management team and coordination of the collaboration.
- Continuation of the High Rigidity Spectrometer (HRS) research project at FRIB to maximize the rate of rare neutron-rich nuclei of central importance for understanding the synthesis of heavy elements in cosmic events.

**Nuclear Physics**
**FY 2022 Research Initiatives**

Nuclear Physics supports the following FY 2022 Request Research Initiatives.

(dollars in thousands)

| | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|
| Accelerator Science and Technology Initiative | – | – | 2,074 | +2,074 |
| Artificial Intelligence and Machine Learning | – | 4,000 | 4,000 | – |
| Integrated Computational & Data Infrastructure | – | – | 1,073 | +1,073 |
| Microelectronics | – | – | 518 | +518 |
| Quantum Information Science | 10,300 | 13,347 | 10,866 | -2,481 |
| Reaching a New Energy Sciences Workforce (RENEW) | – | – | 3,000 | +3,000 |
| **Total, Research Initiatives** | **10,300** | **17,347** | **21,531** | **+4,184** |

*Note: The FY 2021 Enacted funding supporting QIS included $3,500,000 of Isotope Production and Applications for Research and Applications support. In FY 2022, support for these activities can be found in the Isotope R&D and Production Program Budget Request.*

**Nuclear Physics**
**Funding**

(dollars in thousands)

| | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|
| **Nuclear Physics** | | | | |
| Medium Energy, Research | 65,479 | 41,110 | 54,083 | +12,973 |
| Medium Energy, Operations | 122,110 | 117,201 | 142,709 | +25,508 |
| **Total, Medium Energy Physics** | **187,589** | **158,311** | **196,792** | **+38,481** |
| Heavy Ion, Research | 37,661 | 36,313 | 48,059 | +11,746 |
| Heavy Ion, Operations | 187,131 | 181,625 | 183,943 | +2,318 |
| Heavy Ion, Projects | 19,520 | 30,180 | 10,213 | -19,967 |
| **Total, Heavy Ion Physics** | **244,312** | **248,118** | **242,215** | **-5,903** |
| Low Energy, Research | 60,398 | 61,763 | 74,341 | +12,578 |
| Low Energy, Operations | 55,739 | 79,379 | 107,831 | +28,452 |
| Low Energy, Projects | 10,600 | 16,000 | 18,040 | +2,040 |
| **Total, Low Energy Physics** | **126,737** | **157,142** | **200,212** | **+43,070** |
| Theory, Research | 51,862 | 61,129 | 60,781 | -348 |
| **Total, Nuclear Theory** | **51,862** | **61,129** | **60,781** | **-348** |
| Isotopes Operations | 34,400 | 36,340 | – | -36,340 |
| Isotopes Research | 11,500 | 26,660 | – | -26,660 |
| Isotopes Projects | 3,600 | 3,000 | – | -3,000 |
| **Total, Isotope Development and Production for Research and Applications** | **49,500** | **66,000** | **–** | **-66,000** |
| **Subtotal, Nuclear Physics** | **660,000** | **690,700** | **700,000** | **+9,300** |

| | (dollars in thousands) | | | |
|---|---|---|---|---|
| | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
| **Construction** | | | | |
| 14-SC-50, Facility for Rare Isotope Beams (FRIB), MSU | 40,000 | 5,300 | – | -5,300 |
| 20-SC-51, U.S. Stable Isotope Production and Research Center (SIPRC), ORNL | 12,000 | 12,000 | – | -12,000 |
| 20-SC-52, Electron Ion Collider (EIC), BNL | 1,000 | 5,000 | 20,000 | +15,000 |
| **Subtotal, Construction** | **53,000** | **22,300** | **20,000** | **-2,300** |
| **Total, Nuclear Physics** | **713,000** | **713,000** | **720,000** | **+7,000** |

SBIR/STTR funding:

- FY 2020 Enacted: SBIR $18,257,000 and STTR $2,468,000
- FY 2021 Enacted: SBIR $18,685,000 and STTR $2,625,000
- FY 2022 Request: SBIR $21,005,000 and STTR $2,955,000

## Nuclear Physics
## Explanation of Major Changes

| | (dollars in thousands) FY 2022 Request vs FY 2021 Enacted |
|---|---|
| **Medium Energy Physics** | **+38,481** |

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 3,790 operating hours (90 percent optimal), to exploit the capabilities afforded by the 12 GeV CEBAF Upgrade to address the highest priority scientific opportunities; funding is invested to improve the performance of the machine. 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 investments in maintenance activities and cryomodule refurbishment at CEBAF to improve the performance and reliability of the machine. 12 GeV researchers from national laboratories and universities will implement, commission, and operate high priority new experiments at CEBAF. Scientists play a leading role in the development of scientific instrumentation and accelerator components for the EIC. The Request includes support to participate in the Accelerator Science and Technology initiative, and the SC QIS initiative. Activities are continued in Data Analytics to develop pilot platforms targeting automated optimization of accelerator performance. Funding is also requested to initiate participation in the SC initiative on Microelectronics to support R&D for detector materials, devices, advances in front-end electronics, and integrated sensor/processor architectures, including testing and modeling to contribute to microelectronics resilience in severe high radiation environments.

| | |
|---|---|
| **Heavy Ion Physics** | **-5,903** |

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 2,310 hour run (at 90 percent of the capped FY 2022 maximum operations to allow for sPHENIX installation), 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 to complete the 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 includes support for the Accelerator Science and Technology initiative and the SC QIS initiative. Activities are continued in Data Analytics to develop pilot platforms targeting automated optimization of accelerator performance. 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 2022 Request vs FY 2021 Enacted** |
| **Low Energy Physics** | **+43,070** |

The Request provides support for operations of two low energy user facilities: the ATLAS facility, which operates for 5,800 hours (93 percent optimal), and FRIB, which in its first year of operation for scientific research, provides beam time for 2,310 hours (100% of optimal) to support research, beam studies, and commissioning. FRIB research is supported with high priority as FRIB transitions from project completion to an operating Scientific User Facility. 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 double beta decay 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.

The Request provides support for the Accelerator Science and Technology initiative and the SC QIS initiative. Activities are continued in Data Analytics to develop pilot platforms targeting automated optimization of accelerator performance.

| | |
|---|---|
| **Nuclear Theory** | **-348** |

Funding for Nuclear Theory supports 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 redistributes 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 to other relevant subprograms in NP. The Request continues support for Data Analytics that explores platforms for automated machine operations; some of these funds are distributed to other subprograms to recognize the experimental contributions to this effort. Funding is requested for participation in the Integrated Computational & Data Infrastructure initiative to explore cross-cutting cloud solutions to Big Data storage challenges in Nuclear Physics. Funding also supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem.

| | (dollars in thousands) **FY 2022 Request vs FY 2021 Enacted** |
|---|---|
| **Isotope Development and Production for Research and Applications**<br>Funding for the Isotope Development, Production, Research and Applications Subprogram is moved to the new Isotope R&D and Production Program (DOE Isotope Program) in FY 2022. In the 2020 Office of Science restructuring, the DOE IP was pulled out of the Office of Nuclear Physics into its own Program in the Office of Science. | **-66,000** |
| **Construction**<br>The Request provides funding for the EIC to continue Project Engineering and Design. | **-2,300** |
| **Total, Nuclear Physics** | **+7,000** |

**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 innovative 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, as well to meet emerging challenges such as generating new nuclear data relevant for space exploration. 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).

**Program Accomplishments**

*A Landmark Advance on the Road to Quantum Computing.*

Classical computers work by solving complex logic using electronic "bits" that can be in a logical state of 0 or 1. It is also possible to prepare a quantum mechanical two-state system or "qubit" such as e.g. an electron with its spin up or down. The difference is, for the probabilistic quantum mechanical case, it is also possible for the electron to be in a coherent superposition of both states simultaneously. That difference is key to Quantum Computing (QC)—a revolutionary new paradigm for future computers that will be capable of solving problems intractable with today's capabilities. The viability of QC depends in part on how long such coherent superpositions can be sustained. Over the past 20 years, superconducting qubit coherence times have increased more than five orders of magnitude, from less than one nanosecond to more than 100 microseconds. Nonetheless, far longer coherence times are needed. Nuclear physicists from MIT and Pacific Northwest National Laboratory recently made a landmark discovery that ionizing radiation from environmental radioactive materials, contaminants and cosmic rays can limit superconducting qubits to coherence times in the millisecond regime—far too short for practical quantum computing. This finding has implications for the design of future QC facilities where radiation shielding may be needed to reduce the flux of ionizing radiation and increase superconducting qubit coherence times.

*Mass Limit on the Elusive Neutrino is Cut in Half.*

Nuclear physicists from the University of Washington, the University of North Carolina, MIT, Carnegie Mellon University, LBNL, and other international institutions recently cut the upper bound on the neutrino mass in half, demonstrating that the wispy neutrino mass is no more than the energy equivalent of one electron volt (eV)— five-hundred-thousand times less than the mass of an electron. Working on the KATRIN experiment located in Karlsruhe, Germany, the team of scientists is urgently pressing to achieve the lowest limit possible, as the existence of neutrino mass contradicts a prediction of the Standard Model of particle physics and knowing its value opens a window to discovering new physics. Over the next 5 years, KATRIN is expected to further improve its sensitivity by a factor of five.

*An Exciting Future Just Around the Corner.*

The Facility for Rare Isotope Beams (FRIB) recently accelerated an Argon-36 beam to 204 MeV/nucleon corresponding to 57 percent of the speed of light. With a design goal of 200 MeV/nucleon this milestone demonstrates that the FRIB superconducting linear accelerator operates as intended, with the ability to create over 80% of the isotopes predicted to possibly exist in nature—1000 of which have never been produced. Scheduled for on-time completion in FY 2022, FRIB will enable research opportunities for a worldwide community of over 1,500 scientists.

*Something Good from Something Broken.*

Broken symmetries in the early universe account today for the presence of stars, planets and people. For instance, the spontaneous breaking of "chiral symmetry" gives rise to pions— particles that carry the strong force between protons and neutrons, binding them into the nuclei of atoms which account for 98% of the mass of the visible universe. Recently, the PrimEx-II experiment at Thomas Jefferson National Accelerator Facility made an ultra-precise measurement of the lifetime of the pion and compared it with theoretical predictions of modern-day chiral symmetry breaking, confirming our understanding of the origin of the pion and ruling out alternative explanations of why its lifetime is so short.

*Computing the Structure of Nuclei—Faster is a lot Better.*
For nearly a century, nuclear physicists have sought to uncover the elusive properties of the interaction that binds protons and neutrons into atomic nuclei. Theoretical calculations on this question are very time consuming if precise, and for heavy nuclei may even be intractable using the best high-performance computers. It is therefore very exciting that nuclear physicists at Oak Ridge National Laboratory have now developed a new method that accurately emulates the quantum properties of atomic nuclei within a few milliseconds of computing. After an initial training stage using the Oak Ridge Leadership Computing Facility, millions of predictions can now be generated e.g. for the ground-state energy and charge radius of oxygen-16 in a couple of hours on a standard laptop using statistical methods. The results provide invaluable new insights into how protons and neutrons interact with each other in order to bind atomic nuclei.

*Probing the Mystery of Globular Clusters: Direct Measurement of* $^{30}Si(p,\gamma)^{31}P$.
NGC 2419 is a so-called globular cluster located in the outer halo of the Milky Way. It is hard to understand its nature because it consists of a group of red giant stars which have, at one and the same time, an anomalously high enrichment in potassium (K), and an unexpected depletion in magnesium (Mg). This puzzling Mg-K anticorrelation cannot be explained within the standard picture of cluster evolution, and hints at the existence of multiple stellar populations. Researchers at Triangle Universities Nuclear Laboratory's Low Energy Nuclear Astrophysics (LENA) facility have recently measured a key reaction which may shed light on this question by letting protons impinge on silicon nuclei ($^{30}Si$) resulting in the production of a phosphorus nuclei ($^{31}P$) accompanied by a gamma ray. Their results suggest the rate for this reaction, $^{30}Si(p,\gamma)^{31}P$, in the cosmos is ten time less than previously assumed. Precise knowledge of reaction rates and elemental abundances in globular clusters provides unique insights into the evolution of the early Galaxy.

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

**Description**
The Medium Energy 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?

Scientists use various experimental approaches 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. In addition, 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 combinations of quarks and gluons 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. 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 addressing an outstanding grand challenge question of modern physics: 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 EIC is the facility planned to address this science and will be located at BNL; DOE approved CD-0, Approve Mission Need, in December 2019. CEBAF is partnering with BNL to develop and implement the EIC. 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 within the Accelerator Science and Technology Initiative pursue next generation ion source developments and advanced approaches in superconducting radiofrequency (SRF) technology. Accelerator scientists also pursue accelerator science aimed at improving the operations of existing facilities and developing next-generation facilities for nuclear physics. Nuclear physicists participate in activities related to quantum information science (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. Scientists develop cutting-edge techniques based on Data Analytics 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 machine learning (ML) and control and the optimization of accelerator systems operations and detector design using data analytics models. Scientists participate in the SC initiative on Microelectronics research and development.

The subprogram 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 Request also includes funding to meet other obligations, such as the Office of Science Lawrence Awards and Fermi Awards. In FY 2022, SC plans to confer up to 10 awards with honorariums of $20,000 each for the Ernest Orlando Lawrence Award.

<u>Research</u>

The Research activity supports 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 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 in coordination with NIH and homeland security. Scientists are engaged in experimental QIS research. TJNAF staff focus on the 12 GeV experimental program, including implementation of select experiments, acquisition of data, and data analysis at 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 from universities and laboratories advance technology and core competencies essential for improving operations of the complex NP Scientific User Facilities or developing new NP facilities. Activities in the SC Accelerator Science and Technology initiative build on the unique expertise of NP accelerator scientists to develop transformative technology for the Nation, including next-generation accelerator ion sources, innovative, efficient and cost effective cryogenic systems, high gradient SRF cavities, novel in-situ plasma processing of cryomodules, and advancements in hadron beam cooling. Researchers are also engaged in developing learning techniques focused on improving efficiencies of accelerator operations.

Operations

The Operations activity provides Accelerator Operations funding for CEBAF which boasts world unique features of continuous wave polarized beam to four experimental halls and serves over 1,600 U.S. and international users. Funding for this activity supports 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 planned operations run is initiated late in FY 2021 and extends into FY 2022, leading to two distinct running periods in FY 2022; the late operations start in FY 2021 is driven by the installation schedule of a new cryogenics system to address failing components, the cost-effectiveness of a single run that crosses a fiscal year boundary, and COVID impacts. Investments in cryomodule refurbishment, spares and critical maintenance are prioritized to address and improve machine performance and reliability. The Request supports high priority accelerator improvements aimed at providing enhanced capabilities, and high priority capital equipment for research and facility instrumentation. 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 upgrade of the 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.

**Activities and Explanation of Changes**

(dollars in thousands)

| FY 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Medium Energy Physics** | **$158,311** | **$196,792** | **+$38,481** |
| Research | $41,110 | $54,083 | +$12,973 |
| Funding supports scientists, resident at TJNAF, RHIC, universities, and other 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. Funding enables continued targeted analysis of RHIC polarized proton beam data to learn more about the origin of the proton's spin. Funding supports the development of concepts for detectors to be used at the EIC and further develops the scientific program. Funding also enables researchers to pursue accelerator science pertinent to improving current operations of NP facilities including applications of artificial intelligence. | | The Request will continue to support core research. Scientists, resident at TJNAF, RHIC, universities, and other national laboratories, will participate 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 and accelerator science. The Request will continue 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 detector design to be used at the EIC and further develop the scientific program. The Request will increase opportunities for researchers to pursue transformative accelerator science to improve operations of current and future NP facilities including applications of data analytics, and it will provide initial support for the SC Accelerator Science and Technology Initiative. Research on Microelectronics is initiated to study detector materials, devices, advances in front-end electronics, and integrated sensor/processor architectures. Scientists conduct research on quantum sensors to enable precision NP measurements, development of quantum sensors based on atomic-nuclear interactions. | The Request increases funding for participation in SC Initiatives, including QIS, Data Analytics, Microelectronics, and the Accelerator Science and Technology Initiative. Funding will restore core scientific workforce at universities and national laboratories conducting research related to CEBAF, RHIC, EIC and other facilities. |

(dollars in thousands)

| FY 2021 Enacted | | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| Operations | $117,201 | $142,709 | +$25,508 |
| Funding for operations of the CEBAF facility supports the continuation of the high priority experiments in the 12 GeV science program. Funding initiates a long physics run late in the fiscal year which extends into FY 2022 providing 780 operational hours for research, tuning, and beam studies in FY 2021. The cryogenics systems experienced increasing rates of failure, and new critical cryogenics systems are installed in FY 2021, limiting the operations of the machine. Funding supports CEBAF operations, including mission readiness of the accelerator, all power and consumables of the site, cryogenics plant, activities to reduce Helium consumption, activities to improve accelerator performance, high priority facility and instrumentation capital equipment, high priority accelerator improvement and GPP projects, and the key computing capabilities for data taking and analysis. Funding also supports maintenance of critical core competencies and accelerator scientists, engineers, and technicians, and operations staff. Funding supports 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. Funding also supports the participation of accelerator scientists in accelerator R&D activities, including those for the EIC. | | The Request for operations of the CEBAF facility will support the continuation of the high priority experiments in the 12 GeV science program. The Request will provide 3,790 operational hours (90% optimal) for research, tuning, and beam studies. The Request will support CEBAF operations, including mission readiness of the accelerator, all power and consumables of the site, cryogenics plant, activities to reduce helium consumption, activities to improve accelerator performance and reliability, 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. | The Request will increase CEBAF run time hours to approximately 90 percent of optimal operations. The Request prioritizes equipment and effort to improve CEBAF reliability and performance. |

*Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.*

## Nuclear Physics
## Heavy Ion 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 quantum chromodynamics (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 (QGP) 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 demonstrating a first order 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 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. In 2018, a National Academies study gave a strong endorsement to a U.S.-based Electron-Ion Collider (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, and in January 2020, BNL was selected as the location for the EIC. Scientists and accelerator physicists from the Heavy Ion and the Medium Energy sub-programs are partnering to advance the EIC, both playing significant leadership roles in the development of the scientific agenda and implementation of the EIC.

Over the course of the implementation of the EIC, RHIC operations funding will decrease as some scientific staff, engineers and technicians move from RHIC operations to the EIC project. This is a gradual movement to balance the need for the scientific and technical experts with RHIC while ramping up the EIC project. These individuals represent the scientific and

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

technical workforce that are essential to the operations of a complex facility like RHIC and eventually, the EIC. They have critical core competencies in collider operations that cannot easily be replaced; their support is embedded in the EIC TPC funding and they represent the core facility operations force of RHIC and the EIC. Throughout the EIC project, the temporary reprioritization of funds from the collider facility operations budget to the construction budget will reduce the amount of "new funds" needed to implement the EIC, enabling a cost-effective path forward to the implementation of this world-leading facility.

Brookhaven National Laboratory was chosen to host one of the five SC QIS Research Centers in FY 2020 and will focus on building the fundamental tools necessary for the United States to create quantum computers that provide a true advantage over their classical counterparts. Scientists working in heavy ion physics leverage discovery opportunities in sensing, simulation, and computing at the intersections of nuclear physics and QIS.

The SC Accelerator Science and 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 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 Data Analytics applications in optimizing operation of complex accelerators and detectors at user facilities. This research is essential for maintaining 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.

Research

This activity supports high priority research at universities and at BNL, LBNL, LANL, and ORNL to participate in efforts at RHIC and the LHC. NP fully supports U.S. commitments to the LHC "common funds", fees based on the level of U.S. scientist participation in the LHC program and the use of LHC computing capabilities, enabling the participation of researchers in the complementary heavy ion program at CERN. U.S. scientists work with their international peers in developing and implementing upgrades to the LHC scientific instrumentation. Heavy Ion research also supports the SC QIS Centers competitively chosen for support starting in FY 2020, in partnership with the other SC programs.

The university and national laboratory research groups support personnel and graduate students for taking data within the RHIC heavy ion program, analyzing data, publishing results, 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. Scientists participate in the development of a world-leading scientific program for the future EIC.

Transformative accelerator R&D efforts are pursued within the Accelerator Science and Technology initiative, including advancements in hadron beam cooling and SRF technology. Scientists and engineers also pursue accelerator science aimed at improving the operations of existing facilities and developing next-generation facilities for nuclear physics. Scientists develop cutting-edge techniques based on Data Analytics of relevance to nuclear science research, accelerator facility operations and automated machine operations. 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 machine learning (ML) and control and the optimization of accelerator systems operations and detector design using data analytics models.

Operations

The Heavy Ion Operations 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 2022 Request supports high priority capital equipment and accelerator improvement projects at RHIC to promote enhanced and robust operations. In FY 2022, the only detector operating at RHIC will be STAR; PHENIX operations funding is redirected to complete and install the sPHENIX MIE, in preparation for the last RHIC data taking campaign.

RHIC operations have led to advances in accelerator physics which have, in turn improved RHIC performance and enhanced 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 the EIC, 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.

In FY 2022, funding for RHIC operations will decrease as some scientific staff, and experienced accelerator collider engineers and technicians move from RHIC operations to the EIC project. This is a gradual movement, to occur throughout the EIC project, to balance the need for the scientific experts with RHIC while ramping up the EIC project. These individuals represent the scientific and technical workforce that are essential to the operations of a complex facility like RHIC and eventually, the EIC. They have critical core competencies in collider operations that cannot easily be replaced and represent a part of the core facility operations workforce of RHIC and the EIC. The temporary reprioritization of funds from the collider facility operations budget to the construction budget will prioritize funding needed to implement the EIC, enabling a cost-effective path forward to the implementation of this world-leading facility.

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 supported by NASA for the study of space radiation effects applicable to human space flight as well as electronics.

Projects

RHIC scientists and engineers focus on completing and installing sPHENIX in preparation for the last RHIC data taking campaign. 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. Other Project Costs for the EIC support scientists and accelerator physicists to advance the Conceptual Design and conduct accelerator and detector R&D. 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 technical risks and value engineering. The EIC OPC funding supports experienced scientists and engineers skilled in collider operations who were previously supported with RHIC base operations and who are essential for the operations of the current and future upgraded collider.

## Activities and Explanation of Changes

(dollars in thousands)

| FY 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Heavy Ion Physics** | **$248,118** | **$242,215** | **-$5,903** |
| Research | $36,313 | $48,059 | +$11,746 |
| Funding supports scientists resident at RHIC, universities and other 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 also enables scientists to continue to fabricate the sPHENIX MIE for the study of high rate particle jets. Funding also supports modest and cost effective upgrades at STAR in preparation for a polarized proton run in 2022. U.S. scientists participate in the highest priority heavy ion efforts at the international ALICE, CMS, and ATLAS LHC experiments, and the funding supports upgrades at these facilities. Funding supports targeted accelerator R&D relevant to NP programmatic needs. | | The Request will support scientists resident at RHIC, universities and other national laboratories to develop, fabricate, implement and maintain scientific instrumentation; participate in experimental runs to acquire data; analyze data and publish experimental results; develop scientific plans and instrumentation for the EIC; and train students in nuclear science. 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 high priority heavy ion efforts and instrumentation upgrades at the international ALICE, CMS, and ATLAS LHC experiments. The Request will support accelerator R&D relevant to NP programmatic needs and participation in the SC Accelerator Science and Technology initiative. Research activities support the SC QIS Research Centers and data analytics aimed at applications of artificial neural networks to nuclear physics research and the optimization of accelerator performance. | Increased funding will restore the core scientific workforce at universities and national laboratories to enhance high priority research at RHIC, the LHC, and for EIC science and detector development. Heavy ion research supports the SC QIS Research Centers. Funding will support NP participation in high priority SC initiatives, including the Accelerator Science and Technology initiative and data analytics. Funding will support the LHC “common funds” to enable individual U.S. scientist participation in the LHC program and the use of LHC computing capabilities. |

(dollars in thousands)

| FY 2021 Enacted | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|
| Operations $181,625 | $183,943 | +$2,318 |
| Funding supports RHIC operations for 3,130 hours (100 percent optimal). Operating hours of 3,130 are lower than the typical hours RHIC can operate, however, the operating hours are capped in FY 2021 due to planned installation requirements. Funding also 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, 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 maintains critical core competencies and accelerator scientists, engineers, and technicians, for RHIC operations and EIC design. Limited operations funding is redirected to the sPHENIX MIE. Accelerator scientists participate in high priority accelerator R&D. | The Request will support RHIC operations at 2,310 hours (90 percent optimal, which in FY 2022 is capped by installation work for the sPHENIX MIE). The Request 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 provide critical core competencies and accelerator scientists, engineers, and technicians, for collider operations. Accelerator scientists conduct research aimed at improving the operations of the RHIC accelerator complex. | In FY 2022, funding for RHIC operations will allow for 2,310 hours, completion of the sPHENIX upgrade and installation, as well as the move of some scientific staff, engineers, and technicians from RHIC operations to the EIC project. This is a gradual movement to balance the need for the scientific experts with RHIC while ramping up the EIC project. |

(dollars in thousands)

| FY 2021 Enacted | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|
| Projects $30,180 | $10,213 | -$19,967 |
| The FY 2021 Enacted Appropriation includes support for both the sPHENIX MIE, which will study high rate particle jets, and EIC OPC. | The sPHENIX MIE will be completed and installed in FY 2022 to enable the use of precision, high rate jet measurements to further characterize the 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. Also, the experienced scientists and engineers skilled in collider operations continue to transition from RHIC operations to support EIC activities. | RHIC scientists, engineers and technicians will be redirected to the EIC project as some RHIC activities start to ramp down. The requested funding for the sPHENIX MIE will reduce according to the budget profile. EIC OPC will decrease as effort transitions to TEC. |

*Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.*

## Nuclear Physics
## Low Energy Physics

### Description

The Low Energy Nuclear Physics subprogram includes two scientific activities 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 activities address 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 activities also measure 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.

ATLAS, at ANL, is an SC scientific user 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 (SRF) 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. Investments to increase ATLAS capabilities provide unique research opportunities include a new technological approach to the CARIBU ion source and a cost-effective Multi-User Upgrade (MUU) to address a backlog of compelling experiments.

FRIB, completing construction at Michigan State University (MSU) in FY 2022, will advance understanding of the atomic nucleus 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. FRIB became an SC User Facility in FY 2020 and transitions to operations for research data taking in FY 2022. 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 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, enabling the most sensitive experiments across the entire chart of nuclei with the most neutron-rich nuclei available.

In coordination with other SC programs, accelerator scientists in this activity participate in the SC Accelerator Science and Technology initiative and support NP's role in strengthening U.S. supply chain robustness stewarding key technologies such as next generation electron ion source developments and advanced approaches in SRF technology that underpin U.S. leadership and competitiveness in accelerator R&D. Scientists also participate in Data Analytics, providing support for R&D to develop pilot platforms targeting automated optimization of accelerator availability, performance and operation as well as software enabling data-analytics-driven discovery.

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 to discover Elements 119 and 120. All 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 modest 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 activities address these questions through precision studies using neutron and electron beams and decays of nuclei, including beta decay, double-beta decay, and NLDBD. 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), Karlsruhe Tritium Neutrino Experiment (KATRIN)), and in 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.

Scientists in this activity, particularly with their expertise in rare signal events, engage in QIS and quantum computing (QC), and contribute to 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.

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 design, fabricate, install and commission instrumentation at FRIB and prepare for the initiation of the scientific program. Funds transition the most critical key researchers that used to be supported by NSF at the National Superconducting Cyclotron Laboratory (NSCL) to this DOE portfolio to lead the FRIB scientific mission. The Request continues the GRETA MIE, which will be re-baselined after lower than planned FY 2021 funding; and maintains the HRS research 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. Accelerator scientists participate in transformative accelerator R&D, particularly in the development of the next generation ion source for accelerators. Scientists utilize Data Analytics that can promote automated platforms to improve machine performance and reliability.

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 is sensitive to a wide range of underlying new physics and is a test of charge-parity violation, and other experiments at the SNS FNPB continue. First-generation NLDBD experiments finalize analysis of 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. Researchers conduct NP research of relevance to QIS, with a focus on novel quantum sensors.

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 have been increased with the addition of the Electron Beam Ion Source (EBIS), the 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. Accelerator scientists continue the implementation of a neutron-generator based source for CARIBU (nuCARIBU) to improve the stability and intensity of CARIBU beams.

The ATLAS facility nurtures a core competency in accelerator science with SRF 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 MUU Accelerator Improvement Project which will significantly increase the beam hours available for experiments to the scientific community.

The Request ramps up funding to support FRIB operations in FY 2022, when commissioning of the scientific program will begin. The funds transition the most critical operations staff as accelerator components are completed on the project and effort is redirected towards 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 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Low Energy Physics** | **$157,142** | **$200,212** | **+$43,070** |
| Research | $61,763 | $74,341 | +$12,578 |
| Funding supports high priority university and laboratory nuclear structure and nuclear astrophysics efforts at ATLAS and development of the FRIB scientific program including research support for FRIB scientific personnel. Scientists participate in the characterization of recently discovered elements and search for new ones. Research continues at the university-based Centers of Excellence at TUNL, CENPA, and TAMU. | | The Request will support high priority university and laboratory nuclear structure and nuclear astrophysics efforts at ATLAS and installation and commissioning of instrumentation for the FRIB scientific program. The Request will target research for critical FRIB scientific personnel to lead the scientific program at FRIB. 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. Accelerator scientists will develop the next generation ion source for accelerators. Scientists utilize Data Analytics that can promote automated platforms to improve machine performance and reliability. | The Request will restore high priority research efforts and essential workforce at universities and national laboratories, with a focus on conducting experiments at ATLAS and initial physics runs at FRIB. Funding will support high priority research initiatives, including QIS, data analytics, and Accelerator Science and Technology. |
| High priority research in NLDBD continues with CUORE, LEGEND-200, and nEXO. Funding continues support for U.S. participation in the operations of the international KATRIN experiment. | | High priority research in NLDBD will continue with CUORE, LEGEND-200, and nEXO. The Request will continue support for U.S. participation in the operations of the international KATRIN experiment. | |

(dollars in thousands)

| FY 2021 Enacted | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|
| Operations $79,379 | $107,831 | +$28,452 |
| Funding supports operations of ATLAS at 5,350 hours (93 percent optimal hours; note that optimal hours were reduced due to COVID impacts), and provides 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 sustains operations of the 88-Inch Cyclotron for high priority experiments studying newly discovered elements. Funding supports high priority activities necessary to prepare for FRIB operations in FY 2022. | ATLAS operates for 5,800 hours (93 percent of optimal), an increase in hours relative to FY 2021. The Request will fund operations, 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. The Request will also support the first year of 2,310 hours of operations (100% of optimal) at FRIB to initiate the scientific program. Funding will sustain operations of the 88-Inch Cyclotron for high priority experiments studying newly discovered elements. | Requested funding will support FRIB operations, enabling initiation of the physics program and transfer of key personnel to the FRIB Operations team. Increased funding for ATLAS prioritizes increased operation hours. |
| Projects $16,000 | $18,040 | +$2,040 |
| Funding supports the GRETA MIE, MOLLER MIE, NLDBD MIE, and HRS research project. MOLLER achieved CD-1 in FY 2021. GRETA is assessing funding impacts to the project plans. | The Request will continue support for the GRETA MIE, Moller MIE, NLDBD MIE and HRS research project. GRETA and HRS will be supported at their FY 2021 Enacted levels. | The funding increase will mainly support the Moller MIEs. |

*Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.*

## 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 quantum chromodynamics (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 five 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 NNDC is designated as an SC Public Reusable Research (PuRe) Data Resource, a designation commensurate with high standards of data management, resource operation, and scientific impact. 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 quantum information science (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, R&D on nuclear physics techniques to enhance qubit coherence times, and development of quantum computing algorithms applied to quantum mechanical systems and NP topical problems. In partnership with the other SC programs, NP continues support in jointly stewarding SC QIS Research Centers which will focus on building the fundamental tools necessary for the United States to create quantum computers that provide a true advantage over their classical counterparts.

Scientists will develop cutting-edge techniques based on data analytics of relevance to nuclear science research, and accelerator facility operations. 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 machine learning (ML) and control and the optimization of accelerator systems operations and detector design using artificial intelligence (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 lattice quantum chromodynamics (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.

The Nuclear Theory subprogram supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem. The Request includes funding for RENEW in the theory program and it will be distributed across the other subprograms, depending on peer review results of proposals.

<u>Research</u>
This activity supports high priority research at ANL, BNL, LANL, LBNL, LLNL, ORNL, and TJNAF and universities. 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 continues support of topical collaborations within available funds to bring together theorists to address specific emerging and 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 to optimize the interpretation of the experimental results.

The Request redistributes support for research related to QIS and QC to provide technological and computational advances relevant to NP and other fields to other NP subprograms, in recognition of the experimental facets of QIS; overall, the NP Request for QIS increases in FY 2022. 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 are completed in FY 2021, and a new competition will make awards for SciDAC-5 in FY 2022. In addition to addressing specific problems relevant for nuclear physics research, SciDAC projects continue to serve as a water-shed for training scientists who can address national needs.

Funding for data analytics, which has synergies with AI/ML research, continues in FY 2022. These activities help develop cutting-edge techniques based on AI of relevance to nuclear science research, accelerator facility operations, and automated machine operations. In addition, theorists explore cross-cutting cloud solutions to Big Data storage challenges in Nuclear Physics with participation in the SC Integrated Computational & Data Infrastructure Initiative; the significant volumes of data collected from RHIC, CEBAF, FRIB and the future EIC pose particular challenges to the NP community.

The Request expands support for the activities of the USNDP to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development, providing for world-leading acquisition and dissemination of high quality data for public consumption. U.S. efforts focus on improving the completeness and reliability of data already archived that is used for industry and for a variety of Federal missions, and the USNDP expands the effort to conduct experiments needed 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. NP will collaborate with other Federal Agencies that are members of the NP-led Inter-Agency Nuclear Data Working Group, to carry out experimental measurements.

[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 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Nuclear Theory** | **$61,129** | **$60,781** | **-$348** |
| Research | $61,129 | $60,781 | -$348 |
| Funding supports high priority QIS efforts. LQCD computing investments continue 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 fifth and final year of SciDAC-4 grants and the final year of theory topical collaborations initiated in FY 2017. Funding targets investments in an initiative to develop cutting-edge AI techniques of relevance to nuclear science research, accelerator facility operations, and automated machine operations. | | 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 first year of SciDAC-5 grants and theory topical collaborations. Funding will target investments in an initiative to develop cutting-edge data analytics techniques of relevance to nuclear science research, and accelerator facility operations. Theorists participate in the Computational and Data Infrastructure Initiatives to explore solutions to Big Data storage. This activity also supports the RENEW initiative to provide undergraduate and graduate training opportunities for students and academic institutions not currently well represented in the U.S. S&T ecosystem. | Funding for QIS and data analytics are partially distributed to other NP subprograms; overall in NP, the total investment for QIS will increase and the investment in data analytics is flat. Funding will also support participation in two other SC initiatives: the Integrated Computational & Data Infrastructure Initiative and the RENEW Initiative. |

(dollars in thousands)

| FY 2021 Enacted | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|
| Funding supports 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 critical experimental measurements to address gaps in existing nuclear data. | The Request will expand USNDP efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. | Support for experimental nuclear data efforts of the USNDP will increase. |

*Note: Funding for the subprogram above, includes 3.65% of research and development (R&D) funding for the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs.*

**Nuclear Physics**
**Isotope Development and Production for Research and Applications**

## Description

The Isotope Development and Production for Research and Applications subprogram (DOE Isotope Program, or DOE IP) is now a separate program. Please refer to the Isotope R&D and Production Program Budget Request.

**Nuclear Physics**
**Isotope Development and Production for Research and Applications**

## Activities and Explanation of Changes

(dollars in thousands)

| FY 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Isotope Development and Production for Research and Applications** | **$66,000** | **$ —** | **-$66,000** |
| Research | $26,660 | $ — | -$26,660 |
| Funding supports 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 increases 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 continues the development of full scale processing and technology for the production of alpha-emitters for cancer therapy, such as Ac-225. Funding increases for 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. Funding also increases to expand the University 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 continue. Research to develop enrichment capability for new isotopes of importance increase. | | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. |

(dollars in thousands)

| FY 2021 Enacted | FY 2022 Request | Explanation of Changes<br>FY 2022 Request vs FY 2021 Enacted |
|---|---|---|
| Operations $36,340 | $ — | -$36,340 |
| 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. 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 are maintained. Funding continues 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. Funding supports 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. | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. |
| Projects $3,000 | $ — | -$3,000 |
| Funding supports research and development and conceptual design OPC activities of the U.S. SIPRC construction project | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. | Beginning in the FY 2022 Request, the Isotope Development and Production for Research and Applications subprogram is now a separate program. Funds are requested under the new Isotope R&D and Production Program within the Office of Science. |

## 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. The FY 2022 Request continues the construction effort for the Electron-Ion Collider (EIC). The estimated Total Project Cost (TPC) range for the EIC project, which is to be located at Brookhaven National Laboratory (BNL), is $1.7 billion to $2.8 billion. BNL has teamed with Thomas Jefferson National Accelerator Facility (TJNAF) to lead the development and implementation of the EIC. The EIC scope, cost, and schedule include an electron injector chain, an electron storage ring, modifications to one of the two Relativistic Heavy Ion Collider (RHIC) ion accelerators, and one interaction region with a colliding beam detector. The plan also allows for a second interaction region and its detector, although they are not part of the project scope. The project is expected to attract international collaboration and contribution.

Over the course of the implementation of the EIC, the activities of experienced RHIC scientists, engineers and technicians will be redirected to the EIC TPC as RHIC activities start to ramp down. These individuals represent the scientific and technical workforce that are essential to the operations of a complex facility like RHIC and eventually, the EIC. They have critical core competencies in collider operations that cannot easily be replaced and represent a part of the core facility operations workforce of RHIC and the EIC. The temporary reprioritization of funds from the collider facility operations budget to the construction budget will prioritize funding needed to implement the EIC, enabling a cost-effective path forward to the implementation of this world-leading facility.

Since the 2002 Long Range Plan (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 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. 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.

## Nuclear Physics
## Construction

### Activities and Explanation of Changes

(dollars in thousands)

| FY 2021 Enacted | | FY 2022 Request | Explanation of Changes FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|
| **Construction** | **$22,300** | **$20,000** | **-$2,300** |
| 20-SC-51, U.S. Stable Isotope Production and Research Center (SIPRC), ORNL | $12,000 | $ — | -$12,000 |
| Funding supports 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. | | Funds will be requested under the new Isotope R&D and Production Program within the Office of Science. | Funds will be requested under the new Isotope R&D and Production Program within the Office of Science. |
| 20-SC-52, Electron Ion Collider (EIC), BNL | $5,000 | $20,000 | +$15,000 |
| Funding continues TEC 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. RHIC operations includes a "reprioritization" of expert workforce from the RHIC facilities operations budget to support the EIC OPC and TEC request. | Funding will support ongoing engineering and design efforts. |
| 14-SC-50, Facility for Rare Isotope Beams (FRIB), MSU | $5,300 | $ — | -$5,300 |
| Funding supports the completion of cryomodule installation, experimental systems installation, and testing. Funding also continues commissioning efforts associated with technical components as they are completed. This is the final year of funding. Project completion is planned in FY 2022. | | No funding planned in FY 2022. | The FY 2021 Enacted reflects the final year of funding for FRIB. |

## Nuclear Physics
## Capital Summary

(dollars in thousands)

| | Total | Prior Years | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|---|
| **Capital Operating Expenses** | | | | | | |
| Capital Equipment | N/A | N/A | 30,291 | 34,243 | 30,411 | -3,832 |
| Minor Construction Activities | | | | | | |
| General Plant Projects | N/A | N/A | 9,616 | 1,579 | 1,626 | +47 |
| Accelerator Improvement Projects | N/A | N/A | 7,268 | 8,456 | 5,159 | -3,297 |
| **Total, Capital Operating Expenses** | **N/A** | **N/A** | **47,175** | **44,278** | **37,196** | **-7,082** |

## Capital Equipment

(dollars in thousands)

| | Total | Prior Years | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|---|
| **Capital Equipment** | | | | | | |
| Major Items of Equipment | | | | | | |
| Heavy Ion Physics | | | | | | |
| Super Pioneering High Energy Nuclear Interaction Experiment (sPHENIX) | 20,573 | 5,310 | 9,520 | 5,530 | 213 | -5,317 |
| Low Energy Physics | | | | | | |
| Gamma-Ray Energy Tracking Array (GRETA), LBNL | 58,400 | 12,300 | 6,600 | 6,600 | 6,600 | – |
| High Rigidity Spectrometer | 97,940 | 240 | 1,000 | 3,000 | 3,000 | – |
| MOLLER | 46,050 | – | 2,000 | 5,000 | 7,000 | +2,000 |
| Ton-Scale Neutrinoless Double Beta Decay (NLDBD) MIE | 234,540 | – | 1,000 | 1,400 | 1,440 | +40 |
| Isotope Development and Production for Research and Applications | | | | | | |
| Stable Isotope Production Facility (SIPF), ORNL | 25,500 | 24,000 | 1,500 | – | – | – |
| Total, MIEs | N/A | N/A | 21,620 | 21,530 | 18,253 | -3,277 |
| Total, Non-MIE Capital Equipment | N/A | N/A | 8,671 | 12,713 | 12,158 | -555 |
| **Total, Capital Equipment** | **N/A** | **N/A** | **30,291** | **34,243** | **30,411** | **-3,832** |

*Note:*

- *The High Ridgity Spectrometer (HRS) is not an MIE, but a research project supported on a cooperative agreement with Michigan State University.*
- *The Capital Equipment table includes MIEs located at a DOE facility with a Total Estimated Cost (TEC) > $5M and MIEs not located at a DOE facility with a TEC >$2M.*

**Minor Construction Activities**

(dollars in thousands)

| | Total | Prior Years | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|---|
| **General Plant Projects (GPP)** | | | | | | |
| GPPs (greater than or equal to $5M and less than $20M) | | | | | | |
| End Station Refrigerator | 9,500 | – | 9,500 | – | – | – |
| Total GPPs (greater than or equal to $5M and less than $20M) | N/A | N/A | 9,500 | – | – | – |
| Total GPPs less than $5M | N/A | N/A | 116 | 1,579 | 1,626 | +47 |
| **Total, General Plant Projects (GPP)** | **N/A** | **N/A** | **9,616** | **1,579** | **1,626** | **+47** |
| **Accelerator Improvement Projects (AIP)** | | | | | | |
| AIPs (greater than or equal to $5M and less than $20M) | | | | | | |
| FRIB Isotope Harvesting | 5,500 | – | 2,000 | 3,500 | – | -3,500 |
| Total AIPs (greater than or equal to $5M and less than $20M) | N/A | N/A | 2,000 | 3,500 | – | -3,500 |
| Total AIPs less than $5M | N/A | N/A | 5,268 | 4,956 | 5,159 | +203 |
| **Total, Accelerator Improvement Projects (AIP)** | **N/A** | **N/A** | **7,268** | **8,456** | **5,159** | **-3,297** |
| **Total, Minor Construction Activities** | **N/A** | **N/A** | **16,884** | **10,035** | **6,785** | **-3,250** |

**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 on 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 have been 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 2022 Request for sPHENIX of $213,000 is the final year of TEC funding. SC is assessing the impact of COVID on project performance.

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

*Gamma-Ray Energy Tracking Array (GRETA) MIE*

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. CD-2/3 was obtained October 7, 2020 with a TPC of $58,300,000. The FY 2022 Request for GRETA is below the CD-2/3 baseline at $6,600,000 of TEC funding. SC is assessing the impact of constrained funding in FY 2021. SC is assessing the impact of COVID on project performance.

*High Rigidity Spectrometer (HRS) Research Project*

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 is being funded through a cooperative agreement with MSU and is not a capital asset (MIE). CD-0 was approved November 2018. CD-1 was approved in September 2020, with a TPC range of $85,000,000 to $111,400,000. The FY 2022 Request for the HRS of $3,000,000 will support the management team, coordination of collaboration activities and allow preliminary engineering and design work towards future critical decision points.

Low Energy Nuclear Physics: Fundamental Symmetries MIEs:

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

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, several demonstrator efforts using smaller volumes of isotopes and various technologies (bolometry in tellurium dioxide (TeO2) crystals, light collection in liquid xenon, 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 $10^{25}$ years. The goal of a next generation ton-scale experiment is to reach a lifetime limit of $10^{28}$ 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 to $250,000,000. The FY 2022 Request of $1,440,000 will support the management team and collaboration activities. SC is assessing the impact of COVID on project performance.

*Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) MIE*

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. CD-1 was approved in December 2021 with a TPC range of $42,000,000 to $60,100,000. The 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 FY 2022 Request for MOLLER of $7,000,000 is the third year of TEC funding.

## Nuclear Physics
## Construction Projects Summary

(dollars in thousands)

| | Total | Prior Years | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|---|
| **20-SC-51, U.S. Stable Isotope Production and Research Center, ORNL** | | | | | | |
| Total Estimated Cost (TEC) | 24,000 | – | 12,000 | 12,000 | – | -12,000 |
| Other Project Cost (OPC) | 5,600 | 500 | 2,100 | 3,000 | – | -3,000 |
| **Total Project Cost (TPC)** | **29,600** | **500** | **14,100** | **15,000** | **–** | **-15,000** |
| **20-SC-52, Electron Ion Collider** | | | | | | |
| Total Estimated Cost (TEC) | 2,061,000 | – | 1,000 | 5,000 | 20,000 | +15,000 |
| Other Project Cost (OPC) | 187,650 | – | 10,000 | 24,650 | 10,000 | -14,650 |
| **Total Project Cost (TPC)** | **2,248,650** | **–** | **11,000** | **29,650** | **30,000** | **+350** |
| **14-SC-50, Facility for Rare Isotope Beams (FRIB), Michigan State University** | | | | | | |
| Total Estimated Cost (TEC) | 635,500 | 590,200 | 40,000 | 5,300 | – | -5,300 |
| **Total Project Cost (TPC)** | **635,500** | **590,200** | **40,000** | **5,300** | **–** | **-5,300** |
| | | | | | | |
| **Total, Construction** | | | | | | |
| **Total Estimated Cost (TEC)** | **N/A** | **N/A** | **53,000** | **22,300** | **20,000** | **-2,300** |
| **Other Project Cost (OPC)** | **N/A** | **N/A** | **12,100** | **27,650** | **10,000** | **-17,650** |
| **Total Project Cost (TPC)** | **N/A** | **N/A** | **65,100** | **49,950** | **30,000** | **-19,950** |

*Notes:*

- *The total for the U.S. Stable Isotope Production and Research Center (SIPRC) of $29,600,000 does not include $220,400,000 included in the Isotopes R&D and Production program beginning in FY 2022. All future requests for SIPRC will be through the Isotope R&D and Production Program.*
- *The total for FRIB 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.*

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

(dollars in thousands)

| | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|
| Research | 223,300 | 225,191 | 233,455 | +8,264 |
| Facility Operations | 399,380 | 414,545 | 434,483 | +19,938 |
| Projects | | | | |
| Line Item Construction (LIC) | 65,100 | 49,950 | 30,000 | -19,950 |
| Major Items of Equipment (MIE) | 21,620 | 21,530 | 18,253 | -3,277 |
| **Total, Projects** | **86,720** | **71,480** | **48,253** | **-23,227** |
| Other | 3,600 | 1,784 | 3,809 | +2,025 |
| **Total, Nuclear Physics** | **713,000** | **713,000** | **720,000** | **+7,000** |

**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.

**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 2020 Enacted | FY 2020 Current | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|
| **Scientific User Facilities - Type A** | | | | | |
| **Relativistic Heavy Ion Collider** | **193,678** | **192,799** | **187,527** | **191,519** | **+3,992** |
| Number of Users | 990 | 1,007 | 1,010 | 1,010 | – |
| Achieved Operating Hours | – | 4,041 | – | – | – |
| Planned Operating Hours | 3,260 | 3,700 | 3,130 | 2,310 | -820 |
| Optimal Hours | 3,700 | – | 3,130 | 2,580 | -550 |
| Percent of Optimal Hours | 88.1% | 88.1% | 100.0% | 90.0% | -10.0% |
| **Continuous Electron Beam Accelerator Facility** | **127,173** | **130,593** | **122,315** | **153,794** | **+31,479** |
| Number of Users | 1,690 | 1,623 | 1,560 | 1,620 | +60 |
| Achieved Operating Hours | – | 2,587 | – | – | – |
| Planned Operating Hours | 2,560 | 2,820 | 780 | 3,790 | +3,010 |
| Optimal Hours | 2,560 | – | 1,890 | 4,220 | +2,330 |
| Percent of Optimal Hours | 100.0% | 100.0% | 41.3% | 90.0% | +48.7% |
| **Facility for Rare Isotope Beams** | **28,500** | **28,500** | **51,825** | **82,106** | **+30,281** |
| Number of Users | – | – | – | 605 | +605 |
| Planned Operating Hours | – | – | – | 2,310 | +2,310 |
| Optimal Hours | – | – | – | 2,310 | +2,310 |
| Percent of Optimal Hours | – | – | – | 100.0% | +100.0% |

| | FY 2020 Enacted | FY 2020 Current | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|---|
| | (dollars in thousands) | | | | |
| **Argonne Tandem Linac Accelerator System** | **25,846** | **27,657** | **24,539** | **26,708** | **+2,169** |
| Number of Users | 340 | 304 | 305 | 305 | – |
| Achieved Operating Hours | – | 4,529 | – | – | – |
| Planned Operating Hours | 5,950 | 5,950 | 5,350 | 5,800 | +450 |
| Optimal Hours | 6,400 | – | 5,780 | 6,250 | +470 |
| Percent of Optimal Hours | 93.0% | 93.0% | 92.6% | 92.8% | +0.2% |
| **Total, Facilities** | **375,197** | **379,549** | **386,206** | **454,127** | **+67,921** |
| Number of Users | 3,020 | 2,934 | 2,875 | 3,540 | +665 |
| Achieved Operating Hours | – | 11,157 | – | – | – |
| Planned Operating Hours | 11,770 | 12,470 | 9,260 | 14,210 | +4,950 |
| Optimal Hours | 12,660 | – | 10,800 | 15,360 | +4,560 |

*Note:*
- *Achieved Operating Hours and Unscheduled Downtime Hours will only be reflected in the Congressional budget cycle which provides actuals.*
- *In FY 2022, the MOLLER MIE (CEBAF) and sPHENIX MIE (BNL) are not included in the funding amounts above.*
- *The FY 2022 Request level for CEBAF funding includes Theory Research funds which are not included in the FY 2020 Enacted ($3,789,000), FY 2020 Current ($3,789,000), and FY 2021 Enacted ($4,222,000) columns.*
- *For FY 2021, FRIB planned operating hours and optimal hours include 800 hours of operations (commissioning) that are supported from FRIB construction funding that are part of the project TPC. FY 2021 is the first year of operations after project completion.*

## Nuclear Physics
## Scientific Employment

| | FY 2020 Enacted | FY 2021 Enacted | FY 2022 Request | FY 2022 Request vs FY 2021 Enacted |
|---|---|---|---|---|
| Number of Permanent Ph.Ds (FTEs) | 839 | 819 | 880 | +61 |
| Number of Postdoctoral Associates (FTEs) | 326 | 328 | 381 | +53 |
| Number of Graduate Students (FTEs) | 530 | 532 | 546 | +14 |
| Number of Other Scientific Employment (FTEs) | 1,030 | 1,029 | 1,003 | -26 |

*Note: Number of Other Scientific Employment (FTEs) include technicians, engineers, computer professionals and other support staff.*

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

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

**Summary**

The FY 2022 Request for the Electron-Ion Collider (EIC) is $20,000,000 of Total Estimated Cost (TEC) funding and $10,000,000 of Other Project Cost (OPC) funding. The current Total Project Cost (TPC) estimate is $1,700,000,000 to $2,800,000,000.

**Significant Changes**

The EIC was initiated in FY 2020. The most recent DOE Order 413.3B approval, Critical Decision (CD)-0, Approve Mission Need, was received on December 19, 2019. In this Project Data Sheet (PDS), the estimated completion date of the EIC has been changed to FY 2033, reflecting the level of FY 2021 Enacted funding and additional schedule contingency as recommended by peer review. In addition, the preliminary TPC has been decreased in this PDS to reflect the preliminary point estimate as opposed to the upper value of the TPC range presented in the FY 2021 PDS.

In FY 2020, the Analysis of Alternatives was completed by the project team and peer reviewed by an independent panel. The EIC has completed conceptual design on January 12, 2021 and is preparing for CD-1, Approve Alternative Selection and Cost Range, planned in the 3Q FY 2021. In FY 2022, the EIC team will focus on preliminary design of the collider machine and detector instrumentation. Of the $30,000,000 TPC funding requested in FY 2022, $20,000,000 in TEC funding will support the development and completion of the preliminary design. $10,000,000 will be needed for research and development (OPC) to validate technical assumptions and to reduce project risk prior to start of construction.

A Federal Project Director (FPD) has been assigned to this project and has approved this project data sheet. The FPD completed Level 3 certification in FY 2021, and Level 4 certification is in process.

**Critical Milestone History**

| Fiscal Year | CD-0 | Conceptual Design Complete | CD-1 | CD-2 | Final Design Complete | CD-3 | CD-4 |
|---|---|---|---|---|---|---|---|
| FY 2021 | 12/19/19 | 4Q FY 2020 | 4Q FY 2020 | 4Q FY 2022 | TBD | 4Q FY 2023 | 4Q FY 2030 |
| FY 2022 | 12/19/19 | 01/12/21 | 3Q FY 2021 | 2Q FY 2023 | 3Q FY 2024 | 3Q FY 2024 | 4Q FY 2033 |

**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

**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 | 340,000 | 2,010,000 | 2,350,000 | 250,000 | N/A | 250,000 | 2,600,000 |
| FY 2022[a] | 413,000 | 1,648,000 | 2,061,000 | 187,650 | N/A | 187,650 | 2,248,650 |

**2. Project Scope and Justification**

**Scope**

The scope of this project is to design and build the EIC at Brookhaven National Laboratory (BNL) that will fulfill the scientific gap as identified in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP). BNL is partnering with Thomas Jefferson National Accelerator Facility (TJNAF) in the implementation of the EIC. The EIC will have performance parameters that include a high beam polarization of >70 percent from both electrons and light ions, and the capability to accommodate ion beams from deuterons to the heaviest stable nuclei. The EIC will also have variable center of mass energies from 20 to 100 GeV and upgradable to 140 GeV, high collision luminosity from $10^{33}$ -$10^{34}$ $cm^{-2}s^{-1}$, one detector and one interaction region at project completion, and the capability for a second interaction region and second detector.

The scope also includes a new electron injection system and storage ring while taking full advantage of the existing infrastructure by modifying the existing hadron facility of the Relativistic Heavy Ion Collider (RHIC) infrastructure at BNL.

The electron system will include a highly polarized room temperature photo-electron gun and a 400 MeV linac to be installed in an existing available straight section of the RHIC tunnel. It will include a transfer line that brings the electrons into the storage ring at the energy of 5 -18 GeV that will be installed in the existing 2.4 mile circular RHIC tunnel.

Modifications to the existing hadron system include the injection, transfer line and storage ring to increase beam energy to 275 GeV. It will include a strong-hadron-cooling system to reduce and maintain the hadron beam emittance to the level needed to operate with the anticipated luminosity of $10^{33}$ -$10^{34}$ $cm^{-2}s^{-1}$.

The interaction region will have superconducting final focusing magnets, crab-cavities and spin rotators to provide longitudinally polarized beams for collisions, where the outgoing particles will be collected by one detector.

An enhanced 2 K liquid helium cryogenic plant is provided for the superconducting radiofrequency cavities, with enhanced water cooling capacity and cooling towers and chillers to stabilize the environment in the existing tunnel. Civil construction will also include electrical systems, service buildings, and access roads.

It is anticipated that non-DOE funding sources such as international collaborations, the National Science Foundation, and the State of New York, will contribute to the EIC Project. The timeframe for commitments by non-DOE contributors will vary throughout the life of the project and become more certain as the project progresses. All non-DOE funding sources will be closely coordinated with the Office of Nuclear Physics and will be incorporated into the project through the change control process once baselined.

**Justification**

The last three Nuclear Science Advisory Committee (NSAC) Long Range Plan (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

[a] The project is pre-CD-2; the estimated cost and schedule shown are preliminary.

highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams. Consistent with that vision, in 2016 NP commissioned a National Academies of Sciences, Engineering, and Medicine 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 Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets.*

Key Performance Parameters (KPPs)

The 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 project performance stretch goal. Achievement of the Threshold KPPs will be a prerequisite for approval of CD-4, Project Completion.

| Performance Measure | Threshold | Objective |
|---|---|---|
| Conventional facilities | BOD for at least 90,000 gross square feet of new construction. | BOD for at least 90,000 gross square feet of new construction. |
| Center-of-Mass | Center-of-mass energy measured in the range of 20 GeV- 100 GeV. | Center-of-mass energy measured in the range of 20 GeV- 140 GeV. |
| Beam Species | Accelerator capable of delivering beams of protons and a heavy nucleus such as Au. | Ability to deliver a versatile choice of beams from protons and light ions to heavy ions such as Au. |
| Detector system | Detector installed and ready for beam operations. | Inelastic scattering events in the e-p and e-A collisions measured in Detector. |
| Beam Polarization | Hadron beam polarization of > 50% and electron beam polarization of > 40% measured at $E_{cm}$ = 100 GeV. | Hadron beam polarization of > 60% measured at $E_{cm}$ = 100 GeV and electron beam polarization of > 50% measured at $E_{cm}$ = 100 GeV. |
| Luminosity | Luminosity for e-p collisions measured up to $1.0x10^{32}$ $cm^{-2}$ $s^{-1}$. | Luminosity greater than $1.0x10^{33}$ $cm^{-2}$ $s^{-1}$. |

### 3. Financial Schedule

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Total Estimated Cost (TEC)** | | | |
| Design (TEC) | | | |
| FY 2020 | 1,000 | 1,000 | – |
| FY 2021 | 5,000 | 5,000 | 5,750 |
| FY 2022 | 20,000 | 20,000 | 19,750 |
| Outyears | 387,000 | 387,000 | 387,500 |
| **Total, Design (TEC)** | **413,000** | **413,000** | **413,000** |
| Construction (TEC) | | | |
| Outyears | 1,648,000 | 1,648,000 | 1,648,000 |
| **Total, Construction (TEC)** | **1,648,000** | **1,648,000** | **1,648,000** |
| Total Estimated Cost (TEC) | | | |
| FY 2020 | 1,000 | 1,000 | – |
| FY 2021 | 5,000 | 5,000 | 5,750 |
| FY 2022 | 20,000 | 20,000 | 19,750 |
| Outyears | 2,035,000 | 2,035,000 | 2,035,500 |
| **Total, TEC** | **2,061,000** | **2,061,000** | **2,061,000** |

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Other Project Cost (OPC)** | | | |
| FY 2020 | 10,000 | 10,000 | 6,120 |
| FY 2021 | 24,650 | 24,650 | 24,150 |
| FY 2022 | 10,000 | 10,000 | 12,000 |
| Outyears | 143,000 | 143,000 | 145,380 |
| **Total, OPC** | **187,650** | **187,650** | **187,650** |

(dollars in thousands)

| | Budget Authority (Appropriations) | Obligations | Costs |
|---|---|---|---|
| **Total Project Cost (TPC)** | | | |
| FY 2020 | 11,000 | 11,000 | 6,120 |
| FY 2021 | 29,650 | 29,650 | 29,900 |
| FY 2022 | 30,000 | 30,000 | 31,750 |
| Outyears | 2,178,000 | 2,178,000 | 2,180,880 |
| **Total, TPC** | **2,248,650** | **2,248,650** | **2,248,650** |

**4. Details of Project Cost Estimate**

(dollars in thousands)

| | Current Total Estimate | Previous Total Estimate | Original Validated Baseline |
|---|---|---|---|
| **Total Estimated Cost (TEC)** | | | |
| Design | 298,000 | 250,000 | **N/A** |
| Design - Contingency | 115,000 | 90,000 | **N/A** |
| **Total, Design (TEC)** | **413,000** | **340,000** | **N/A** |
| Construction | 1,177,000 | 1,490,000 | **N/A** |
| Construction - Contingency | 471,000 | 520,000 | **N/A** |
| **Total, Construction (TEC)** | **1,648,000** | **2,010,000** | **N/A** |
| **Total, TEC** | **2,061,000** | **2,350,000** | **N/A** |
| *Contingency, TEC* | *586,000* | *610,000* | ***N/A*** |
| **Other Project Cost (OPC)** | | | |
| R&D | 46,650 | 30,000 | **N/A** |
| Conceptual Design | 11,000 | 40,000 | **N/A** |
| Other OPC Costs | 93,000 | 115,000 | **N/A** |
| OPC - Contingency | 37,000 | 65,000 | **N/A** |
| **Total, Except D&D (OPC)** | **187,650** | **250,000** | **N/A** |
| **Total, OPC** | **187,650** | **250,000** | **N/A** |
| *Contingency, OPC* | *37,000* | *65,000* | ***N/A*** |
| **Total, TPC** | **2,248,650** | **2,600,000** | **N/A** |
| ***Total, Contingency (TEC+OPC)*** | ***623,000*** | ***675,000*** | ***N/A*** |

### 5. Schedule of Appropriations Requests

(dollars in thousands)

| Request Year | Type | Prior Years | FY 2020 | FY 2021 | FY 2022 | Outyears | Total |
|---|---|---|---|---|---|---|---|
| FY 2021 | TEC | — | 1,000 | 1,000 | — | — | — |
| | OPC | — | 10,000 | 1,500 | — | — | — |
| | TPC | — | 11,000 | 2,500 | — | — | — |
| FY 2022 | TEC | — | 1,000 | 5,000 | 20,000 | 2,035,000 | 2,061,000 |
| | OPC | — | 10,000 | 24,650 | 10,000 | 143,000 | 187,650 |
| | TPC | — | 11,000 | 29,650 | 30,000 | 2,178,000 | 2,248,650 |

### 6. Related Operations and Maintenance Funding Requirements

Over the course of the implementation of the EIC, NP will redirect experienced RHIC scientists, engineers, and technicians from RHIC operations to the EIC project. This is a gradual movement to balance the need for the scientific experts with RHIC while ramping up EIC project. These individuals represent the scientific and technical workforce that are essential to the operations of a complex facility like RHIC and eventually, the EIC. They have critical core competencies in collider operations that cannot easily be replaced, and they represent the core facility operations force of RHIC and the EIC. In the FY 2022 Request, RHIC Operations includes a "reprioritization" of expert workforce from the RHIC facility operations budget to support the EIC OPC and TEC request. The temporary reprioritization of funds from the facility operations budget to the construction budget will reduce the amount of "new funds" needed to implement the EIC, enabling a cost-effective path forward to the implementation of this world-leading facility. As the EIC nears CD-4 when the machine will be restarted, the scientists, engineers and technicians that are needed to operate the EIC will be transferred back to the facility operations budget.

| | |
|---|---|
| Start of Operation or Beneficial Occupancy | 4Q FY 2031 |
| 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, Maintenance and Repair | TBD | TBD | TBD | TBD |

### 7. D&D Information

As part of the upgrade and renovation of the existing accelerator facilities, up to 200,000 square feet of industrial space will be built as service buildings to house mechanical and electrical equipment.

| | Square Feet |
|---|---|
| New area being constructed by this project at BNL | 200,000 |
| Area of D&D in this project at BNL | 0 |
| Area at BNL to be transferred, sold, and/or D&D outside the project, including area previously "banked" | N/A |
| Area of D&D in this project at other sites | N/A |
| Area at other sites to be transferred, sold, and/or D&D outside the project, including area previously "banked" | N/A |
| Total area eliminated | 0 |

### 8. Acquisition Approach

SC selected Brookhaven National Laboratory (BNL) as the site for the EIC on January 9, 2020. NP will approve the Acquisition Strategy in conjunction with CD-1. DOE will utilize the expertise of the Managing and Operating contractors at BNL and TJNAF to manage the project including the design, fabrication, monitoring cost and schedule, and delivering the technical performance specified in the KPPs. A certified Earned Value Management System already exists at both Laboratories and will be implemented to evaluate project progress and to ensure consistence with DOE O 413.3B, Program and Project Management for the Acquisition of Capital Assets.