Nuclear Physics

Overview

The mission of the Nuclear Physics (NP) program is to explore one of the enduring mysteries of the universe, the nature of matter: its basic constituents and how they interact to form the elements and the properties we observe. Solving this mystery involves 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, climate, 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 recently 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 scientific 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 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 artificial intelligence and machine learning, 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 a scientific user facility, with data taking for scientific research initiated 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 approximately 95 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 artificial intelligence and machine learning which can benefit nuclear physics research and NP accelerator operations. NP also stewards accelerator research and development (R&D), pursuing next generation electron ion source developments and advancing approaches in superconducting radio frequency (SRF) technologies. In addition, the request supports NP participation in the following SC Initiatives: Microelectronics, Reaching a New Energy Sciences Workforce (RENEW), Funding for Accelerated, Inclusive Research (FAIR), and Accelerate Innovations in Emerging Technologies (Accelerate).

Highlights of the FY 2023 Request

The FY 2023 Request for $739.2 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
  - Exploring the fundamental structure of nucleons at the sub-femtometer scale at CEBAF and the future EIC
  - 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 its 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 leading to precision predictions from QCD of nuclear properties and nuclear reactions via Scientific Discovery Through Advanced Computing
  - Curation of reliable, accurate Nuclear Data for basic nuclear research and nuclear technologies
  - Niche capabilities and unique "hands-on" experiences in nuclear science at NP supported University Centers of Excellence
- *Quantum Information Science (QIS)*: Support continues for the SC National QIS Research Centers (NQISRCs) 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.*
- *Artificial Intelligence and Machine Learning (AI/ML)*: As part of the Office of Science's initiative on AI/ML, 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.
- *Reaching a New Energy Sciences Workforce (RENEW)*: NP continues support for 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.
- *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.
- *Funding for Accelerated, Inclusive Research (FAIR):* The FAIR initiative will provide focused investment on enhancing

research on clean energy, climate, and related topics at minority serving institutions, including attention to underserved and environmental justice communities. The activities will improve the capability of MSIs to perform and propose competitive research and will build beneficial relationships between MSIs and DOE national laboratories and facilities.

- *Accelerate Innovations in Emerging Technologies (Accelerate):* The Accelerate initiative will support scientific research to accelerate the transition of science advances to energy technologies. The goal is to drive scientific discovery to sustainable production of new technologies across the innovation continuum, to provide experiences in working across this continuum for the workforce needed for industries of the future, and to meet the nation's needs for abundant clean energy, a sustainable environment, and national security.

<u>Facility Operations</u>

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

- RHIC operates 3,264 hours (90 percent optimal) to begin the sPHENIX scientific program.
- CEBAF operates for 3,840 hours (91 percent of optimal), enabling highest priority 12 GeV experiments.
- ATLAS operates for 5,952 hours (93 percent of optimal) to enable the most compelling experiments in nuclear structure and astrophysics.
- FRIB operations continues to grow towards full operations as it enters its first full year of user experiments, operating for 3,100 hours (91 percent of optimal).

<u>Projects</u>

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

- Continuation of research and Project Engineering and Design (PED) activities for the Electron-Ion Collider (EIC).
- Continuation of the Gamma-Ray Energy Tracking Array (GRETA) MIE, to enable provision of advanced, high resolution gamma ray detection capabilities for FRIB.
- 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 (TSNLDBD) 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 2023 Research Initiatives

Nuclear Physics supports the following FY 2023 Request Research Initiatives.

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Accelerate Innovations in Emerging Technologies	–	–	4,000	+4,000
Artificial Intelligence and Machine Learning	4,000	4,000	8,000	+4,000
Funding for Accelerated, Inclusive Research (FAIR)	–	–	2,000	+2,000
Microelectronics	–	–	518	+518
Quantum Information Science	13,347	9,847	10,866	-2,481
Reaching a New Energy Sciences Workforce (RENEW)	–	–	6,000	+6,000
Total, Research Initiatives	**17,347**	**13,847**	**31,384**	**+14,037**

Notes:
- *The FY 2021 Enacted funding supporting QIS included $3,500,000 of Isotope Production and Applications for Research and Applications support. Beginning in FY 2022, support for these activities can be found in the Isotope R&D and Production Program Budget Request.*
- *The Integrated Computational and Data Initiative is rolled into Advanced Computing Initiative in FY 2023.*

Nuclear Physics
Funding

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Nuclear Physics				
Medium Energy, Research	41,110	43,800	50,305	+9,195
Medium Energy, Operations	117,201	117,201	143,443	+26,242
Total, Medium Energy Physics	**158,311**	**161,001**	**193,748**	**+35,437**
Heavy Ion, Research	36,313	36,313	43,204	+6,891
Heavy Ion, Operations	181,625	183,552	191,782	+10,157
Heavy Ion, Projects	30,180	24,863	10,000	-20,180
Total, Heavy Ion Physics	**248,118**	**244,728**	**244,986**	**-3,132**
Low Energy, Research	61,763	61,763	68,059	+6,296
Low Energy, Operations	79,379	79,379	125,471	+46,092
Low Energy, Projects	16,000	16,000	23,940	+7,940
Total, Low Energy Physics	**157,142**	**157,142**	**217,470**	**+60,328**
Theory, Research	61,129	61,129	62,992	+1,863
Total, Nuclear Theory	**61,129**	**61,129**	**62,992**	**+1,863**
Isotopes Operations	36,340	–	–	-36,340
Isotopes Research	26,660	–	–	-26,660
Isotopes Projects	3,000	–	–	-3,000
Total, Isotope Development and Production for Research and Applications	**66,000**	**–**	**–**	**-66,000**
Subtotal, Nuclear Physics	**690,700**	**624,000**	**719,196**	**+28,496**

(dollars in thousands)

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Construction				
14-SC-50, Facility for Rare Isotope Beams (FRIB), MSU	5,300	–	–	-5,300
20-SC-51, U.S. Stable Isotope Production and Research Center (SIPRC)	12,000	–	–	-12,000
20-SC-52, Electron Ion Collider (EIC), BNL	5,000	5,000	20,000	+15,000
Subtotal, Construction	**22,300**	**5,000**	**20,000**	**-2,300**
Total, Nuclear Physics	**713,000**	**629,000**	**739,196**	**+26,196**

SBIR/STTR funding:

- FY 2021 Enacted: SBIR $18,685,000 and STTR $2,625,000
- FY 2022 Annualized CR: SBIR $19,564,000 and STTR $2,748,000
- FY 2023 Request: SBIR $21,450,000 and STTR $3,015,000

Nuclear Physics
Explanation of Major Changes

	(dollars in thousands) FY 2023 Request vs FY 2021 Enacted
Medium Energy Physics 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 CEBAF accelerator to support 3,840 operating hours (91 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 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 SC QIS initiative. Activities are continued in AI/ML to develop pilot platforms targeting automated optimization of accelerator performance. Funding is also requested to participate 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 and low temperature environments. This subprogram also supports the Accelerate initiative which will support scientific research to accelerate the transition of science advances to energy technologies.	**+35,437**
Heavy Ion Physics 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 3,264 hour run (at 90 percent optimal), high priority core competencies, and experimental activities to prepare scientific instrumentation and infrastructure for the scientific program. The Request supports commissioning and initial operation of the super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX), 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 the SC QIS initiative. Activities are continued in AI/ML 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.	**-3,132**

(dollars in thousands)

	FY 2023 Request vs FY 2021 Enacted
Low Energy Physics	**+60,328**

The Request provides support for operations of two low energy user facilities: the ATLAS facility, which operates for 5,952 hours (93 percent optimal), and FRIB, which in its first full year of operation for scientific research, provides beam time for 3,100 hours (91 percent of optimal) to support research and beam studies. FRIB research is supported following FRIB's transition from project completion to operating Scientific User Facility In FY 2022. 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 HRS 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 High Intensity Gamma Source (HIGS) at the Triangle Universities Nuclear Laboratory, and the Center for Experimental Nuclear Physics and Astrophysics (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 TSNLDBD experiment (MIE) to reach unprecedented sensitivities. Funding in Fundamental Symmetries also supports efforts such as the Fundamental Neutron Physics Beamline at the Spallation Neutron Source (SNS) and the continued development of its flagship experiment, the neutron electric dipole moment (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.

Activities continue in AI/ML to develop pilot platforms targeting automated optimization of accelerator performance. Participation in the SC QIS initiative also continues.

	(dollars in thousands) FY 2023 Request vs FY 2021 Enacted
Nuclear Theory 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 distributes 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 AI/ML 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 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. This subprogram also supports the FAIR initiative which will provide focused investment on enhancing research on clean energy, climate, and related topics at minority serving institutions, including attention to underserved and environmental justice regions.	**+1,863**
Isotope Development and Production for Research and Applications In the 2020 Office of Science restructuring, the DOE Isotope Program was pulled out of the Office of Nuclear Physics into its own Program in the Office of Science. Funding for the Isotope Development, Production, Research and Applications Subprogram was moved to the new Isotope R&D and Production Program (DOE Isotope Program) in FY 2022.	**-66,000**
Construction The Request provides funding for the EIC to continue Project Engineering and Design activities.	**-2,300**
Total, Nuclear Physics	**+26,196**

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 LQCD 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. Capabilities and techniques developed for nuclear physics at NP accelerator facilities are used by DOD and NASA to test electronics for radiation sensitivity in furtherance of their missions. NP research develops technological advances relevant to clean energy and 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)); accelerator research and enhancing U.S.-based supply chains for critical accelerator technologies (ARP); and research in developing neutron, gamma, and particle beam sources with applications in cargo screening (NNSA, DHS, and the FBI).

Program Accomplishments

World's Highest Energy Heavy Ion Linear Accelerator Completed: The Facility for Rare Isotope Beams (FRIB), a world leading "microscope" for understanding how protons and neutrons can arrange themselves to form nuclei, the limits of how many species of nuclei can be formed in nature, and how the heaviest nuclei are produced in violent cosmic events, finishes on-time, on-budget construction and will begin early science in spring of 2022. Completing the world's highest energy continuous wave heavy ion accelerator required multiple technological firsts, including a novel high-power target, a high efficiency cryogenic plant, and a novel superconducting radiofrequency resonator system for accelerating a wide range of ion species.

Researching Nuclear Risotto: An interdisciplinary team including nuclear theorists, data scientists, and astronomers has put new limits on the radii of neutron stars with unprecedented accuracy. Neutron stars—one possible final stage in the lives of ordinary stars after their "ordinary matter" has boiled off—consist of the densest matter in the universe. The researchers' approach combined observations of gravitational waves from neutron stars, electromagnetic observations by NASA's Neutron Star Interior Composition Explorer mission and other telescopes, and state-of-the-art theoretical calculations performed at Los Alamos National Laboratory by DOE Nuclear Physics researchers. The results show that typical neutron stars can concentrate approximately 1-2 solar masses in a radius of 11.8 kilometers, placing new stringent constraints on nuclear matter at the limits of existence.

Creating Mass From Energy in the Lab: Although it's been known since Einstein's famous equation $E=mc^2$ that energy and matter are interchangeable, only now have scientists working at the Relativistic Heavy Ion Collider (RHIC) found clear evidence that the collision of two packets of light, called photons, can produce pairs of particles, one matter particle and one antimatter particle—the electron and its antimatter companion—the positron, in this instance. This process was predicted by Gregory Breit and John Wheeler, more than 80 years ago. While e+e- pairs have been produced in high-energy collisions, this observation involved two heavy ions flying past each other at nearly the speed of light without touching. The ultra-high electric field between the two passing nuclei results in photons having enough relative energy to form electron-positron pairs. This result puts focus on an exciting new possibility: lasers being sufficiently energetic to see the Breit-Wheeler process directly, without colliding particle beams.

Rare Carbon Breakup-Mode Constrained for the First Time: Researchers from Texas A&M, LSU, and Washington University at St. Louis have observed, for the first time, the breakup of an excited form of carbon-12 (comprising a nucleus of 6 protons and 6 neutrons) into three so-called alpha-particles (nuclei each containing 2 protons + 2 neutrons). Using a new, highly sophisticated detector at Texas A&M, the direct 3D reconstruction of this three-alpha breakup reaction allowed scientists exceptional insight into the role of the inverse process in synthesizing 12 Carbon and other light nuclei in the early universe.

Heavy Nuclei Have Thick Skins: The PREx Collaboration at the Continuous Electron Beam Accelerator Facility at Thomas Jefferson National Accelerator Facility recently published conclusive evidence confirming that the heavy lead (Pb) nucleus has a neutron skin approximately a third as thick as the radius of the proton—about twice as thick as predicted. The result has deep implications for the physical processes in neutron stars, with connections to recent observations of colliding neutron stars made by the Laser Interferometer Gravitational-Wave Observatory, or LIGO, experiment.

The Quantum Rodeo: Quantum computers offer the potential of solving problems too difficult for classical computers. A team of nuclear physicists have developed a "Rodeo Algorithm for Quantum Computing" offering a new approach, exponentially faster than other well-known algorithms, for preparing energy states of large complex systems on a quantum computer. The Rodeo algorithm is efficient in terms of both computing resources and speed. It requires relatively few qubits and quantum gates, representing a promising future candidate for solving intractable problems in quantum many-body systems vital to nuclear physics, particle physics, condensed matter physics, atomic and molecular systems, and quantum chemistry.

Uncertainty on the Neutron Lifetime is Cut by in Half: Neutrons account for about half of the mass of the matter around us. When inside a nucleus, a neutron is stable. On its own however it is unstable and will decay with a half-life of about 10 minutes. Precisely how long neutrons live is an important quantity in many areas of science, including the accurate description of what happened in the early Universe. High-precision measurements of this lifetime also provide a precise test to probe for new particles and forces beyond what can be measured with colliders like the Large Hadron Collider. A team of researchers from Los Alamos National Laboratory, the Triangle Universities Nuclear Laboratory and several universities has now cut the uncertainty in neutron's lifetime in half using ultracold neutrons from the LANL ultracold neutron source.

Tooling Up to Solve a Major Mystery: The proton is a building block of nature fundamental to everything around us. Despite a century of research however, how the properties of the proton (its mass and spin) are dynamically generated by the quarks and massless gluons inside it remains a mystery. The future Electron-Ion Collider (EIC) aims to solve this mystery by colliding a high-intensity polarized beam of high-energy electrons with protons or larger atomic nuclei. The EIC recently passed a critical milestone, Critical Decision 1 (CD-1), allowing the project to initiate design of the accelerator, detector, and supporting systems. The project to implement the EIC is being carried out by Brookhaven National Laboratory in partnership with Thomas Jefferson National Accelerator Facility.

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 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. 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 Electron-Ion Collider (EIC) facility, to be located at BNL, plans to address this science. DOE approved CD-1, Approve Alternative Selection and Cost Range, in June 2021. TJNAF is partnering with BNL to develop and implement the EIC. Scientists and accelerator physicists, from the Medium Energy subprogram, 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 advanced approaches in superconducting radiofrequency (SRF) technology and 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 artificial intelligence and machine learning (AI/ML) of relevance to nuclear science research and accelerator facility operations. NP continues support for applications of artificial neural networks in the analysis of nuclear physics data. Additionally, NP is supporting technical development at the intersections between real-time ML and control and the optimization of accelerator systems operations and detector design using AI/ML models. Scientists participate in the SC initiative on Microelectronics research and development, emphasizing unique microelectronics that survive in cryogenic and high radiation environments.

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 continues support for honoraria for awards, including the Enrico Fermi Awards and the Ernest Orlando Lawrence Awards.

Research

The Research activity supports high priority research at universities, TJNAF, BNL, ANL, 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 development of scientific and experimental plans for the EIC. 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.

TJNAF Laboratory scientists and many university groups play leadership roles in new experiments in the 12 GeV scientific program, and are engaged in commissioning experiments, instrumentation development, and data taking. Scientists at several national laboratories are engaged in planning for the construction of the EIC and its scientific instrumentation. ANL researchers 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. LANL scientists are leading a new experiment at Fermilab to study whether anti-quarks are in orbit about the spin axis of the proton. 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 at universities and laboratories advance technology and core competencies essential for improving operations of the complex user facilities or developing new facilities within the NP program, including the development of transformative technology for the Nation, including innovative, efficient and cost effective cryogenic systems, high gradient SRF cavities, and novel in-situ plasma processing of cryomodules. Researchers are also engaged in developing ML techniques focused on improving efficiencies of accelerator operations.

This activity also supports the Accelerate initiative which will support scientific research to accelerate the transition of science advances to energy technologies.

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 1,700 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 highest priority investments in cryomodule refurbishment, spares and critical maintenance are supported 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 to improve 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 developed award-winning cryogenics techniques that have led to more cost-effective operations at TJNAF and several other SC facilities; their cryogenics expertise benefitted 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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Medium Energy Physics	**$158,311**	**$193,748**	**+$35,437**
Research	$41,110	$50,305	+$9,195
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 continue to support researchers to pursue transformative accelerator science to improve operations of current and future NP facilities including applications of AI/ML. Research on Microelectronics is continued 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 supports the Accelerate Innovations in Emerging Technologies (Accelerate) initiative.	The Request will support high priority core scientific workforce at universities and national laboratories conducting research related to CEBAF, RHIC, EIC and other facilities, as well as the Accelerate initiative.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Operations $117,201	$143,443	+$26,242
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 3,840 operational hours (91 percent 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 support CEBAF run time hours at approximately 91 percent of optimal operations. Only the highest priority equipment and efforts to improve CEBAF reliability and performance are supported.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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 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 the sPHENIX detector. The sPHENIX detector will be commissioned in FY 2023. 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 more than 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[bbb]. In January 2020, BNL was selected as the location for the EIC and in June 2021, DOE approved CD-1, Approve Alternative Selection and Cost Range. 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 acquisition 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 technical workforce that are essential to the operations of a complex facility like RHIC and eventually, the EIC. They have critical core

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

competencies in collider operations that cannot easily be replaced; their support is embedded in the EIC TPC 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 National Quantum Information Sciences Research Centers (NQISRCs) 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), and ion source technologies. Artificial intelligence and machine learning (AI/ML) applications are pursued to optimize operation of the complex accelerators and detectors at user facilities in the NP program. 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.

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. It will enable the participation of researchers in the complementary heavy ion program at CERN. U.S. scientists will work with their international peers in developing and implementing upgrades to the LHC scientific instrumentation. One such proposed upgrade is the CMS minimum ionizing particle timing detector (MTD) to enhance particle identification for understanding jet quenching, improving heavy flavor hadron measurements, and exploring collectivity in small systems. Heavy Ion research also supports the NQISRCs 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, including advancements in ion source developments, SRF technology, and hadron beam cooling. 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 AI/ML 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 ML and control and the optimization of accelerator systems operations and detector design using AI/ML 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 2023 Request will support high priority capital equipment and accelerator improvement projects at RHIC to promote enhanced and robust operations, such as upgrades to key accelerator infrastructure FY 2023 represents the commissioning of the sPHENIX detector, which will be the key device for the last RHIC data taking campaign. sPHENIX enables 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.

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 2023, funding for RHIC operations continues to be reprioritized to EIC 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 symbiotic, parallel, cost-effective operations of the Brookhaven Linac Isotope Producer Facility (BLIP), supported by the DOE Isotope Program to produce 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 the installation and initiate the commissioning of sPHENIX. Other project costs for the EIC support scientists and accelerator physicists to advance the conceptual design and conduct accelerator and detector R&D. Integration of laboratory core competencies and participation from across the national laboratory complex and universities continues. Accelerator and detector R&D focuses on reduction of technical risks and value engineering. The EIC Other Project Costs (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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Heavy Ion Physics	**$248,118**	**$244,986**	**-$3,132**
Research	$36,313	$43,204	+$6,891
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. 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. Research activities support the NQISRCs and AI/ML aimed at applications of artificial neural networks to nuclear physics research and the optimization of accelerator performance.	Funding will continue to support high priority core scientific workforce at universities and national laboratories to enhance high priority research at RHIC, the LHC, and for EIC science and detector development.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Operations $181,625	$191,782	+$10,157
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 3,264 hours (90 percent optimal). 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.	The Request for RHIC operations will support operations at 90 percent of optimal for commissioning of sPHENIX. RHIC operations in FY 2023 is no longer capped with completion of sPHENIX installation. Reprioritization of effort to support EIC continues.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Projects $30,180	$10,000	-$20,180
The FY 2021 Enacted Appropriation includes support for both the sPHENIX MIE, which will study high rate particle jets, and EIC OPC.	The experienced scientists and engineers skilled in collider operations continue to transition from RHIC operations to support EIC activities.	OPC support of EIC activities will continue. The Request does not include funds for sPHENIX, as construction is completed in FY 2022 and the device undergoes commissioning in FY 2023.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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 Physics subprogram includes two scientific activities that focus on using nuclear interactions and decays to answer overarching questions related to Nuclear Structure and Nuclear Astrophysics, and 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 300 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 Neutron-generator Upgrade to the Californium Rare Ion Breeder Upgrade (nuCARIBU) ion source. Technologically cutting-edge and unique instrumentation are a hallmark of ATLAS, and the facility 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 including a cost-effective Multi-User Upgrade (MUU) to address a backlog of compelling experiments.

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) became an SC scientific user facility in FY 2020 and transitions from construction to operations in FY 2022. It will enter its first full year of operation in FY 2023. FRIB 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 to test the limits of nuclear existence. The Gamma-Ray Energy Tracking Array (GRETA) MIE is one of the primary tools that the nuclear science community has identified as 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 exploit FRIB's fast beam capabilities, enabling the most sensitive experiments across the entire chart of nuclei with the most neutron-rich nuclei available.

Scientists participate in artificial intelligence and machine learning (AI/ML) research, conducting R&D targeting automated optimization of accelerator availability, performance, and operation, as well as software development enabling AI/ML-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 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 Element 120. 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 an 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 super-heavy elements. DOD and NASA exploit materials irradiation capabilities at the 88-Inch Cyclotron 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 four facilities at the Triangle Universities Nuclear Laboratory (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 what role have they played in creating the imbalance between matter and antimatter in our 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 the existence of forces that were present at the dawn of the universe, 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 neutrino-less double beta decay (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 SC steward of neutrino mass measurements and NLDBD. Often in partnership with NSF, NP has invested in neutrino experiments both domestically and overseas, playing critical roles in international experiments that depend on U.S. leadership for their ultimate success: e,g, the Cryogenic Underground Observatory for Rare Events (CUORE, the Karlsruhe Tritium Neutrino Experiment [KATRIN]). In partnership with NSF, NP also 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. The observation of such events would have profound, game changing consequences for present understanding of the physical universe. NP has invested in R&D on candidate technologies for next–generation ton-scale experiments, including crystals of enriched germanium (LEGEND-1000), liquid xenon (nEXO) and lithium molybdenate crystals (CUPID). The Request will provide support for ton-scale research based on one or more of these technologies to progress toward CD-1, Approve Alternative Selection and Cost Range. Ton-Scale NLDBD research is expected to provide unprecedented resolution for the detection of the rare NLDBD process. The NLDBD 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 engaged in Fundamental Symmetries research are particularly well positioned with their expertise in rare signal detection, to engage in research on Quantum Information Science (QIS) and Quantum Computing (QC). They 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 for use in the scientific program initiating in FY 2022. The Request supports leading researchers who worked at other facilities to help lead the FRIB scientific mission. The Request continues the GRETA MIE. It also continues implementation of the High Rigidity Spectrometer. 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 next generation ion sources for accelerators. Scientists utilize AI/ML advances 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 continues 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. Other experiments at the SNS FNPB continue, along with minor construction activities in support of this research. First-generation NLDBD experiments finalize analysis of data, such as the CUORE experiment at Gran Sasso Laboratory in Italy. Conceptual design efforts continue for international ton-scale NLDBD research, 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 nuCARIBU radioactive beam system for accelerated radioactive ion beams, the in-flight radioactive ion separator to increase the intensity of radioactive beams, and a gas-filled analyzer.

The ATLAS facility nurtures a core competency in accelerator science with 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 SC 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 2023, the first full year of operations for the scientific program. The Request supports beam time for the highest priority experiments, improvements to experimental capabilities, and accelerator enhancements to support progress towards reaching full power.

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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Low Energy Physics **$157,142**	**$217,470**	**+$60,328**
Research $61,763	$68,059	+$6,296
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. Scientists utilize AI/ML that can promote automated platforms to improve machine performance and reliability and advance detector design and data processing.	The Request will support the highest 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.
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 a strategic mix of efforts for selection in FY 2022. The Request will continue support for U.S. participation in the operations of the international KATRIN experiment.	

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Operations $79,379	$125,471	+$46,092
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 5,952 hours (93 percent of optimal) 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 second year of operations at FRIB for 3,100 hours (91 percent of optimal) to execute the first full year of 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 the first full year of the physics program, and the highest priority experiments at ATLAS at above 90 percent of optimal.
Projects $16,000	$23,940	+$7,940
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 the HRS research project.	Increase funding will support the GRETA MIE.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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 in the cosmos and what the nature of the neutrino may reveal about the evolution of the early universe.

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, team-based 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 theorists also conduct research related to quantum information science (QIS) and quantum computing (QC). This work is carried out in coordination with and support of other NP/SC efforts including R&D on quantum sensors to enable precision 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 other SC programs, NP continues its role in jointly stewarding NQISRCs which 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 continue to develop cutting-edge techniques based on artificial Intelligence and machine Learning (AI/ML) to accelerate discovery in nuclear science research and optimize the efficiency of accelerator facility operations. NP applications of artificial neural networks in data analysis continue to be enhanced and made more powerful. Future "intelligent" experiments will seek to incorporate next generation AI advances into the optimization of detector design, detector hardware and electronics. The Request also supports technical development at the intersection between real-time ML and control and optimization of accelerator systems operations, with specific focus on improving the reliability and efficiency 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 subprogram as well as the other NP subprograms with the distribution dependent on peer review results of topical proposals.

Research

This activity supports high priority research at ANL, BNL, LANL, LBNL, LLNL, ORNL, 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 varying experimental facets of QIS; overall, the NP Request for QIS continues in FY 2023. 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[ccc] 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.

Within available funding, a new competition in support of SciDAC-5 is planned that will result in new awards in FY 2022. The Request supports the second year of these efforts. In addition to addressing specific problems relevant for nuclear physics research, SciDAC projects continue to serve as critical research for highly trained scientists who can address national needs. A planned competition in support of the next round topical collaborations will result in new awards being made in FY 2022. The Request supports the second year of these efforts as well.

Funding for AI/ML research continues in FY 2023. These activities help develop cutting-edge techniques based on AI of relevance to nuclear science research, accelerator facility operations, and automated machine operations.

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.

This activity also supports the Funding for Accelerated, Inclusive Research (FAIR) initiative which will provide focused investment on enhancing research on clean energy, climate, and related topics at minority serving institutions, including attention to underserved and environmental justice communities.

[ccc] "*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 2023 Request	Explanation of Changes FY 2023 Request vs FY 2021 Enacted
Nuclear Theory **$61,129**	**$62,992**	**+$1,863**
Research $61,129	$62,992	+$1,863
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 second year of SciDAC-5 grants and theory topical collaborations. Funding will target investments in an initiative to develop cutting-edge AI/ML techniques of relevance to nuclear science research, and accelerator facility operations. 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. The Request also supports the FAIR initiative.	Funding will support the highest priority research in nuclear theory, growth of the AI/ML and RENEW initiatives, and the start of the FAIR initiative.

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 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 continue the expanded USNDP efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development initiated in FY 2022.	Funding will support nuclear data efforts of the USNDP.

Note:

- *Funding for the subprogram above, includes 3.65 percent 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.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 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 2023 Request	Explanation of Changes FY 2023 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.

Nuclear Physics
Construction

Description

This subprogram supports all line-item construction for the entire NP program. All Total Estimated Costs (TEC) are funded in this subprogram, including engineering, design, and construction. Other Project Costs (OPC) are funded in the relevant subprograms. The FY 2023 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 contributions.

Over the course of the acquisition 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 later the EIC. The temporary reprioritization of funds from the collider facility operations budget to the construction budget will supplement 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, followed by CD-1, Approve Alternative Selection and Cost Range on June 29, 2021.

Activities and Explanation of Changes

(dollars in thousands)

FY 2021 Enacted	FY 2023 Request	Explanation of Changes FY 2023 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 is requested in FY 2023.	The FY 2021 Enacted reflects the final year of funding for FRIB.

Nuclear Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Capital Operating Expenses						
Capital Equipment	N/A	N/A	33,397	28,080	34,988	+1,591
Minor Construction Activities						
General Plant Projects	N/A	N/A	1,579	1,579	2,642	+1,063
Accelerator Improvement Projects	N/A	N/A	4,956	4,956	5,211	+255
Total, Capital Operating Expenses	**N/A**	**N/A**	**39,932**	**34,615**	**42,841**	**+2,909**

Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Capital Equipment						
Major Items of Equipment						
Heavy Ion Physics						
Super Pioneering High Energy Nuclear Interaction Experiment (sPHENIX)	20,577	14,834	5,530	213	–	-5,530
Low Energy Physics						
Gamma-Ray Energy Tracking Array (GRETA), LBNL	55,300	18,900	6,600	6,600	15,500	+8,900
High Rigidity Spectrometer	101,540	1,240	3,000	3,000	3,000	–
MOLLER	47,100	2,000	5,000	5,000	4,000	-1,000
Ton-Scale Neutrinoless Double Beta Decay (NLDBD) MIE	235,540	1,000	1,400	1,400	1,440	+40
Total, MIEs	N/A	N/A	21,530	16,213	23,940	+2,410
Total, Non-MIE Capital Equipment	N/A	N/A	11,867	11,867	11,048	-819
Total, Capital Equipment	**N/A**	**N/A**	**33,397**	**28,080**	**34,988**	**+1,591**

Notes:
- *The High Rigidity 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 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
General Plant Projects (GPP)						
GPPs (greater than or equal to $5M and less than $20M)						
nEDM Experimental Building 2 (EB-2)	9,257	–	–	–	1,000	+1,000
Total GPPs (greater than or equal to $5M and less than $20M)	N/A	N/A	–	–	1,000	+1,000
Total GPPs less than $5M	N/A	N/A	1,579	1,579	1,642	+63
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**1,579**	**1,579**	**2,642**	**+1,063**
Accelerator Improvement Projects (AIP)						
Total AIPs less than $5M	N/A	N/A	4,956	4,956	5,211	+255
Total, Accelerator Improvement Projects (AIP)	**N/A**	**N/A**	**4,956**	**4,956**	**5,211**	**+255**
Total, Minor Construction Activities	**N/A**	**N/A**	**6,535**	**6,535**	**7,853**	**+1,318**

Note:

- *GPP activities less than $5M include design and construction for additions and/or improvements to land, buildings, replacements or addition to roads, and general area improvements. AIP activities less than $5M include minor construction at an existing accelerator facility.*

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. Final funding for sPHENIX is provided in the FY 2022 Request with the project completing in FY 2023.

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 2023 Request for GRETA is $15,500,000 of TEC funding. NP is assessing the impact of constrained funding in FY 2021 and FY 2022.

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 2023 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. 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 2023 Request of $1,440,000 will support the management team and collaboration activities.

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 2020 with a TPC range of $42,000,000 to $60,100,000. The project is working on preliminary engineering and design in advance of a combined CD-2/3 planned in Q2 of FY 2023. CD-4 is expected in Q4 of FY2027. 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 2023 Request for MOLLER of $4,000,000 will support management, engineering, and design work toward CD-2/3.

Nuclear Physics
Minor Construction Description(s)

General Plant Projects $5 Million to less than $20 Million

Outfitting of Research and Collaborations Spaces
General Plant Project Details

Project Name:	nEDM Experimental Building 2 (EB-2)
Location/Site:	Oak Ridge National Laboratory
Type:	GPP
Total Estimated Cost:	$9,257,032
Construction Design:	$0
Project Description:	Minor construction of an experimental building at Oak Ridge National Laboratory is needed to support neutron electric dipole moment research. This new experimental building will allow researchers to continue the 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.

Nuclear Physics
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 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	2,600	3,000	–	–	-3,000
Total Project Cost (TPC)	**29,600**	**14,600**	**15,000**	**–**	**–**	**-15,000**
20-SC-52, Electron Ion Collider						
Total Estimated Cost (TEC)	2,061,000	1,000	5,000	5,000	20,000	+15,000
Other Project Cost (OPC)	187,650	10,000	24,650	24,650	10,000	-14,650
Total Project Cost (TPC)	**2,248,650**	**11,000**	**29,650**	**29,650**	**30,000**	**+350**
14-SC-50, Facility for Rare Isotope Beams (FRIB), Michigan State University						
Total Estimated Cost (TEC)	635,500	630,200	5,300	–	–	-5,300
Total Project Cost (TPC)	**635,500**	**630,200**	**5,300**	**–**	**–**	**-5,300**
Total, Construction						
Total Estimated Cost (TEC)	**N/A**	**N/A**	**22,300**	**5,000**	**20,000**	**-2,300**
Other Project Cost (OPC)	**N/A**	**N/A**	**27,650**	**24,650**	**10,000**	**-17,650**
Total Project Cost (TPC)	**N/A**	**N/A**	**49,950**	**29,650**	**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 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Research	225,191	201,221	220,799	-4,392
Facility Operations	414,545	380,132	460,696	+46,151
Projects				
Line Item Construction (LIC)	49,950	29,650	30,000	-19,950
Major Items of Equipment (MIE)	21,530	16,213	23,940	+2,410
Total, Projects	**71,480**	**45,863**	**53,940**	**-17,540**
Other	1,784	1,784	3,761	+1,977
Total, Nuclear Physics	**713,000**	**629,000**	**739,196**	**+26,196**

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 2021 Enacted	FY 2021 Current	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Scientific User Facilities - Type A					
Relativistic Heavy Ion Collider	**187,527**	**180,204**	**183,552**	**191,782**	**+4,255**
Number of Users	1,010	917	1,010	1,010	–
Achieved Operating Hours	–	3,410	–	–	–
Planned Operating Hours	3,130	3,130	2,580	3,264	+134
Optimal Hours	3,130	3,130	2,580	3,625	+495
Percent of Optimal Hours	100.0%	100.0%	100.0%	90.0%	-10.0%
Continuous Electron Beam Accelerator Facility	**122,315**	**119,521**	**117,201**	**143,443**	**+21,128**
Number of Users	1,560	1,692	1,620	1,730	+170
Achieved Operating Hours	–	776	–	–	–
Planned Operating Hours	780	780	2,100	3,840	+3,060
Optimal Hours	1,890	1,890	4,220	4,220	+2,330
Percent of Optimal Hours	41.3%	41.3%	49.8%	91.0%	+49.7%
Facility for Rare Isotope Beams	**51,825**	**50,000**	**51,825**	**96,266**	**+44,441**
Number of Users	–	–	400	755	+755
Planned Operating Hours	–	–	600	3,100	+3,100
Optimal Hours	–	–	2,310	3,400	+3,400
Percent of Optimal Hours	–	–	26.0%	91.1%	+91.1%

(dollars in thousands)

	FY 2021 Enacted	FY 2021 Current	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Argonne Tandem Linac Accelerator System	**24,539**	**24,537**	**22,865**	**24,279**	**-260**
Number of Users	305	272	305	340	+35
Achieved Operating Hours	–	5,483	–	–	–
Planned Operating Hours	5,350	5,350	5,800	5,952	+602
Optimal Hours	5,780	5,780	6,250	6,400	+620
Percent of Optimal Hours	92.6%	92.6%	92.8%	93.0%	+0.4%
Total, Facilities	**386,206**	**374,262**	**375,443**	**455,770**	**+69,564**
Number of Users	2,875	2,881	3,335	3,835	+960
Achieved Operating Hours	–	9,669	–	–	–
Planned Operating Hours	9,260	9,260	11,080	16,156	+6,896
Optimal Hours	10,800	10,800	15,360	17,645	+6,845

Notes:
- *Achieved Operating Hours and Unscheduled Downtime Hours will only be reflected in the Congressional budget cycle which provides actuals.*
- *The MOLLER MIE (CEBAF) and sPHENIX MIE (BNL) are not included in the funding amounts above.*
- *For FY 2022, 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 2022 is the first year of operations after project completion.*
- *For FY 2023, the dollar values for the facilities do not include research amounts.*
- *The FY 2021 Current, does not include SBIR/STTR transfers.*

Nuclear Physics
Scientific Employment

	FY 2021 Enacted	FY 2022 Annualized CR	FY 2023 Request	FY 2023 Request vs FY 2021 Enacted
Number of Permanent Ph.Ds (FTEs)	819	819	856	+37
Number of Postdoctoral Associates (FTEs)	328	328	366	+38
Number of Graduate Students (FTEs)	532	532	524	-8
Number of Other Scientific Employment (FTEs)	1,029	1,029	1,023	-6
Total Scientific Employment (FTEs)	**2,708**	**2,708**	**2,769**	**+61**

Note:
- *Other Scientific Employment (FTEs) includes 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 2023 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) range 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)-1, Approve Alternative Selection and Cost Range, was attained on June 29, 2021. In this Project Data Sheet (PDS), the estimated completion date (CD-4) remains 4Q FY 2033 and still considers the additional schedule contingency that was recommended by peer review. In addition, the preliminary TPC in this PDS reflects continued elaboration of the project scope and shows an increase over the point estimate in the FY 2022 PDS, however, the point estimate remains within the cost range. The project is working to CD-2 which is expected in 3Q FY 2023.

The EIC completed conceptual design on January 12, 2021, and achieved CD-1 on June 29, 2021. The project received in December 2021 three detector collaboration proposals with a report recommending a path forward expected in March 2022. In FY 2022, the EIC team will focus on preliminary design of the infrastructure, collider machine, and detector instrumentation. The team is also developing a list of possible long-lead procurements and considering requesting a CD-3A, Approve Long Lead Procurement, in conjunction with CD-2, Approve Performance Baseline. Of the $30,000,000 TPC funding requested in FY 2023, $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
FY 2023	12/19/19	01/12/21	6/29/2021	3Q 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, Total	TPC
FY 2021	340,000	2,010,000	2,350,000	250,000	250,000	2,600,000
FY 2022	413,000	1,648,000	2,061,000	187,650	187,650	2,248,650
FY 2023	413,000	1,648,000	2,061,000	187,650	187,650	2,248,650

Note:

- *This project has not received CD-2 approval; therefore, funding estimates are preliminary.*

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 greater than 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 to 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 planning for 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 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 prior to setting the performance baseline at CD-2. 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, Approve Project Completion.

Performance Measure	Threshold	Objective
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.
Accelerator	Accelerator installed and 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	Detector installed and ready for beam operations.	Inelastic scattering events in the e-p and e-A collisions measured in Detector.
Polarization	Hadron beam polarization of > 50 percent and electron beam polarization of > 40 percent measured at E_{cm} = 100 GeV.	Hadron beam polarization of > 60 percent and electron beam polarization of > 50 percent 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	5,000	5,000	5,000
FY 2023	20,000	20,000	19,500
Outyears	382,000	382,000	382,750
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	5,000	5,000	5,000
FY 2023	20,000	20,000	19,500
Outyears	2,030,000	2,030,000	2,030,750
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	24,650	24,650	26,650
FY 2023	10,000	10,000	11,500
Outyears	118,350	118,350	119,230
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	29,650	29,650	31,650
FY 2023	30,000	30,000	31,000
Outyears	2,148,350	2,148,350	2,149,980
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	291,000	298,000	**N/A**
Design - Contingency	122,000	115,000	**N/A**
Total, Design (TEC)	**413,000**	**413,000**	**N/A**
Construction	1,127,000	1,177,000	**N/A**
Construction - Contingency	521,000	471,000	**N/A**
Total, Construction (TEC)	**1,648,000**	**1,648,000**	**N/A**
Total, TEC	**2,061,000**	**2,061,000**	**N/A**
Contingency, TEC	*643,000*	*586,000*	***N/A***
Other Project Cost (OPC)			
R&D	46,650	46,650	**N/A**
Conceptual Design	11,000	11,000	**N/A**
Other OPC Costs	130,000	93,000	**N/A**
OPC - Contingency	N/A	37,000	**N/A**
Total, Except D&D (OPC)	**187,650**	**187,650**	**N/A**
Total, OPC	**187,650**	**187,650**	**N/A**
Contingency, OPC	***N/A***	*37,000*	***N/A***
Total, TPC	**2,248,650**	**2,248,650**	**N/A**
Total, Contingency (TEC+OPC)	***643,000***	***623,000***	***N/A***

5. **Schedule of Appropriations Requests**

(dollars in thousands)

Fiscal Year	Type	Prior Years	FY 2021	FY 2022	FY 2023	Outyears	Total
FY 2021	TEC	1,000	1,000	—	—	2,348,000	2,350,000
	OPC	10,000	1,500	—	—	238,500	250,000
	TPC	11,000	2,500	—	—	2,586,500	2,600,000
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
FY 2023	TEC	1,000	5,000	5,000	20,000	2,030,000	2,061,000
	OPC	10,000	24,650	24,650	10,000	118,350	187,650
	TPC	11,000	29,650	29,650	30,000	2,148,350	2,248,650

6. **Related Operations and Maintenance Funding Requirements**

Over the course of the acquisition 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 2033
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	167,000	167,000	13,500,000	13,500,000

7. D&D Information

As part of the upgrade and renovation of the existing accelerator facilities, up to 200,000 square feet of new industrial space will be built as service buildings to house mechanical and electrical equipment. The new area being constructed in this project is not replacing existing facilities.

	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 approved 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 based on those that already exist at both laboratories and will evaluate project progress and ensure consistency with DOE Order 413.3B, Program and Project Management for the Acquisition of Capital Assets.