Nuclear Physics

Overview

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

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

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

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

Highly trained scientists who conceive, plan, execute, and interpret transformative experiments are at the heart of the NP program. NP supports these university and national laboratory scientists and U.S. participation in select international collaborations resulting in an average of approximately 90 Ph.D. degrees awarded annually to students for research supported by the program. DOE NP is the steward of the nation's fundamental nuclear physics research portfolio; in FY 2018, DOE provided ~ 91% and NSF ~ 9 % of the total investment in the U.S. nuclear physics basic research portfolio. As documented in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP) for Nuclear Science, *Reaching for the Horizon*[a], over 40% of the scientists who receive Ph.D.'s in nuclear science find careers in sectors other than academia and DOE research laboratories, serving national needs in defense, government, and industry. DOE's mission and priorities guide NP research, which in turn develop the core competencies and expertise needed to achieve the goals of the NP program and train the next generation of nuclear scientists. National laboratory scientists work and collaborate with academic scientists and other national laboratory experimental and theoretical researchers to collect and analyze data, and

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

to construct, support, and maintain the advanced instrumentation and world-class facilities used in experiments. The national laboratories provide state-of-the-art resources for targeted detector and accelerator research and development (R&D) for future upgrades and new facilities. This research develops knowledge, technologies, and trained scientists to design and build next-generation NP accelerator facilities, and is relevant to machines being developed by other domestic and international programs.

The world-class scientific user facilities and associated instrumentation necessary to advance the U.S. nuclear science program are large and complex, and account for a significant portion of the NP budget. NP supports three scientific user facilities: the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL); the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (TJNAF); and the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL). Each of these facilities has unique capabilities that advance the scientific thrusts outlined in the LRP. In FY 2020, these facilities will provide particle beams for an international user community of almost 2,000 research scientists. In FY 2019, approximately 35 percent of these researchers are from institutions outside of the U.S. and they provide very significant benefits, including leveraging the U.S. program through contributed capital, human capital, and experimental equipment, as well as intellectual contributions. Researchers supported by other SC programs such as High Energy Physics (HEP) and Basic Energy Sciences (BES), DOE Offices such as the National Nuclear Security Administration (NNSA) and Nuclear Energy (NE), Federal agencies such as the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD), and industries, use NP scientific user facilities and core competencies to carry out research programs important for their respective missions. The 12 GeV CEBAF Upgrade project, completed in FY 2017 on cost and schedule, offers exciting opportunities to researchers to study quark structure. Construction of the Facility for Rare Isotope Beams (FRIB), a world-class nuclear physics scientific user facility with unique capabilities in nuclear structure and astrophysics, continues at Michigan State University (MSU), according to the baseline cost and schedule. This project is over 89% complete and will provide exciting new capabilities in nuclear structure and astrophysics to better understand the landscape of the periodic table of elements.

The 2015 NSAC LRP for Nuclear Science recommended a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of FRIB. Consistent with that vision, in 2016 NP commissioned a National Academy of Sciences (NAS) study by an independent panel of external experts to assess the uniqueness and scientific merit of such a facility. The report[a], released in July 2018, strongly supports the scientific case for building a U.S.-based EIC, documenting that an EIC will advance the understanding of the origins of nucleon mass, the origin of the spin properties of nucleons, and the behavior of gluons. Further, in 2017 NP commissioned the nuclear physics community to convene a panel of technical experts to carry out a peer review to identify critical R&D needed to reduce risk and establish the basic feasibility of various machine concepts for an EIC. The subsequent 2017 report, Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics[b] (the Jones report), was invaluable in aligning R&D efforts to the highest priority efforts. The FY 2020 Request initiates Other Project Costs (OPC) support for conceptual design and R&D for the EIC.

Involving students in the development and construction of NP facilities and advanced instrumentation, as well as accelerator technology and computational techniques, helps to develop the highly trained workforce needed in the field of nuclear science. In addition to significant advances in discovery science, these facilities and techniques provide collateral benefits such as the creation of new technologies with broad-based applications in industry and society. NP supports short- and mid-term accelerator R&D that is specific to the programmatic needs of its current or planned facilities. In the process, technological advances and core competencies in accelerator science that are developed by NP are also often relevant to other applications and other SC programs. For example, superconducting radio frequency (SRF) particle acceleration developed for NP programmatic missions has provided technological advances for a broad range of applications including materials research, cancer therapy, food safety, bio-threat mitigation, national defense, waste treatment, and commercial fabrication. The Office of Science programs coordinate closely on the different types of accelerator R&D activities to exploit synergies and avoid duplication of efforts.

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

[b]https://science.energy.gov/~/media/np/pdf/Reports/Report_of_the_Community_Review_of_EIC_Accelerator_RD_for_the_Office_of_Nuclear_Physics_20170214.pdf

Highlights of the FY 2020 Request

The FY 2020 Request for $624,854,000 supports the highest priority efforts and capabilities in nuclear science to optimize scientific productivity. Research thrusts and instrumentation and construction initiatives are closely aligned to guidance from National Academy studies and the NSAC LRP. The supported initiatives, infrastructure, scientific user facilities, and R&D efforts maintain U.S. leadership in nuclear science. The Request will continue support for world-class discovery science research and R&D integration to facilitate the development of important new applications for medicine, commerce, and national security. Advances will continue to be enabled by world-class experimental user facilities and Nobel prize-worthy theoretical and experimental nuclear physics research. The Request increases support for quantum information science (QIS) efforts, including quantum computing (QC), for NP experiments and modeling in collaboration with the other SC program offices. This effort includes the development of quantum sensors based on atomic-nuclear interactions and quantum control (coherent control) techniques, the production of stable isotopes for next generation quantum information systems, and the development of quantum computing algorithms.

The DOE Isotope Program will continue to introduce new medical isotopes to the community for clinical trials and cancer therapy, and to support stable isotope enrichment capabilities in the United States to replenish U.S. inventory and reduce foreign dependence on isotopes of strategic importance for the nation. The Request includes an increase to develop new production capabilities for isotopes that are in short supply and of paramount importance for the Nation.

The Request for *Research* supports university and laboratory researchers to nurture critical core competencies and enable high priority theoretical and experimental activities to target compelling scientific opportunities at the frontier of nuclear science, and in concert with guidance from the NAS and the NSAC.
The FY 2020 Request supports world-class research in all scientific thrusts of nuclear science. These include:

- Experimental and theoretical exploitation of the new capabilities enabled by the 12 GeV CEBAF Upgrade to unravel the mechanism of quark confinement;
- Discovery research at RHIC, the nation’s only remaining collider, to search for a critical point in the phase diagram of QCD matter and further characterize the quark-gluon plasma (QGP) discovered at RHIC that last existed at the beginning of the cosmos;
- Targeted collaboration in the heavy ion program at the CERN LHC to provide U.S. researchers the opportunity to investigate states of matter under substantially different initial conditions than those provided by RHIC, providing complementary information regarding the matter that existed during the infant universe;
- The highest priority research in QIS to enable precision nuclear physics measurements, quantum simulations with trapped ions, and quantum computing solutions to otherwise intractable QCD challenges. NP participates in planned coordinated SC QIS research and facility activities;
- Challenging new experiments at ATLAS to study nuclear structure and nuclear reactions occurring under extreme conditions in the cosmos that are conjectured to play a central role in the synthesis of heavy elements;
- Pioneering R&D in neutrino-less double beta decay to determine whether the neutrino is its own anti-particle, a discovery that could fundamentally change current understanding of the physical universe;
- Funding for the initiation of the High Rigidity Spectrometer (HRS) instrumentation for FRIB. The HRS will enable the most sensitive experiments across the entire span of known nuclei, thereby enabling experiments with the most neutron-rich nuclei available at FRIB.
- Impactful studies into the nature of the neutron at the Fundamental Neutron Physics Beamline at the Spallation Neutron Source (SNS), and the development of the high-risk, high-discovery potential Neutron Electric Dipole Moment (nEDM) experiment; that could shed light on why there is more matter than anti-matter in the universe.
- The highest priority accelerator R&D of relevance to NP next-generation machines and to improve the performance of existing machines. Transformative accelerator science activities significantly advance the state-of-the-art in next-generation ion sources, SRF technology, beam physics and advanced materials for accelerators.
- Targeted investments to develop cutting-edge techniques based on Artificial Intelligence (AI) of relevance to nuclear science research, accelerator facility operations and automated machine operations in the DOE Isotope Program.
- Increased forefront isotope R&D to develop new production methods for critical isotopes in high demand for the nation, including isotopes for medicine that could revolutionize therapy for metastasized cancer, and the development of enriched stable isotope production capabilities to reduce the nation’s dependence on foreign supplies and produce isotopes for quantum computing.

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

- Funding supports RHIC to operate for 1,500 hours in FY 2020. The Request allows for an initial run with the completed Low Energy RHIC e-Cooler (LEReC) project, an accelerator improvement project, which will enable new capability to further increase luminosity in order to carry out a definitive search for a critical point in the phase diagram of QCD matter. Investments continue in the highest priority accelerator improvement projects and capital equipment for maintaining operations;
- Funding supports CEBAF to operate for 1,020 hours in FY 2020. This continues the highly anticipated science program of the 12 GeV machine with associated experimental instrumentation. Investments continue in the highest priority accelerator improvement projects and capital equipment for maintaining operations. A one-time increase to General Purpose Plant (GPP) funding is provided to fully fund a critical replacement End Station Refrigerator to mitigate end-of-life risk of current equipment and provide added capacity necessary for future experiments;
- ATLAS operates as the world's premiere stable ion beam facility for 2,090 hours to enable compelling experiments in nuclear structure and astrophysics. Investments continue in the highest priority accelerator improvement projects and capital equipment for maintaining operations;
- Operations funding will be provided to FRIB to partially support the operation of accelerator components as they complete fabrication and commissioning on the project, and the transition of some associated operational staff to the facility operations budget;
- Support is provided for the experimental physics University Centers of Excellence including the Center for Experimental Nuclear Physics and Applications (CENPA) at the University of Washington, the Research and Engineering Center at the Massachusetts Institute for Technology (MIT), the High Intensity Gamma Source (HIGS) at Duke University, and the Texas A&M Cyclotron Institute at the Texas A&M University (TAMU). These Centers provide niche capabilities and unique "hands-on" experiences in nuclear science.
- Funding fully supports mission readiness and nurtures critical core competencies at the isotope production facilities. These facilities produce isotopes in short supply that are critical to the nation's federal complex, research enterprise and industry. University isotope production capabilities are increased and networked into the DOE Isotope Program for the production of high priority short-lived isotopes. Operation of the Enriched Stable Isotope Prototype Plant (ESIPP) increases to replenish U.S. inventory, reduce dependence on foreign suppliers for research quantities of stable isotopes, and produce isotopes for quantum systems. The DOE Isotope Program participates in planned coordinated SC QIS research and facility activities.

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

- Continued construction funding for the Facility for Rare Isotope Beams (FRIB), which will provide world-leading capabilities for nuclear structure and nuclear astrophysics; the project continues to make impressive progress and is over 89% complete. Construction funding continues according to the baselined profile.
- Initiation of engineering design of the U.S. Stable Isotope Production and Research Center (SIPRC) to significantly increase the domestic production capabilities of stable isotopes for scientific, industrial, national security and medical uses.
- Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. Critical Decision-0, *Approve Mission Need*, is planned for FY 2019.
- Continued funding for the Gamma-Ray Energy Tracking Array (GRETA) MIE, which will enable provision of advanced, high resolution gamma ray detection capabilities for FRIB.
- Initiation of the Ton-scale Neutrinoless Double Beta Decay experiment to determine whether the neutrino is its own antiparticle. Critical Decision-0, *Approve Mission Need*, was approved in FY 2019.
- Support final year of funding for the Stable Isotope Production Facility (SIPF) MIE, which will provide increased domestic capability for production of critically needed enriched stable isotopes, and reduce the nation's dependence on foreign supply. While FY 2020 represents the final year of funding, this technically driven funding profile will support completion of the facility in FY 2024.

- Initiation of the Isotope Harvesting accelerator improvement project at FRIB. This modest project will add harvesting capabilities to the FRIB, which will provide access to a wide range of isotopes, including unusual isotopes for exploratory studies.
- Continued funding to support the super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) MIE, which will have enhanced capabilities that will further RHIC's scientific mission by studying high rate jet production. This project will be implemented with funding from within the RHIC facility budget. sPHENIX will be funded at a reduced level relative to the planned profile approved at CD-1/CD-3A.
- Initiation of the Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) MIE, which will measure the parity-violating asymmetry in electron-electron scattering with the 12 GeV CEBAF machine. This experiment will search for evidence of physics beyond our current understanding with unprecedented levels of precision, by comparing extremely small deviations in the outcomes of scattering experiments with the predictions of theory.

Nuclear Physics supports the following FY 2020 Administration Priorities.

FY 2020 Administration Priorities

	(dollars in thousands)
	Quantum Information Science (QIS)
Nuclear Physics	7,000

Nuclear Physics
Funding

	(dollars in thousands)			
	FY 2018 Enacted	**FY 2019 Enacted**	**FY 2020 Request**	**FY 2020 Request vs FY 2019 Enacted**
Medium Energy Nuclear Physics				
Research	40,050	43,286	35,500	-7,786
Operations	112,000	117,390	114,500	-2,890
Other Research	4,152	3,553	2,667	-886
SBIR/STTR	19,248	19,961	18,633	-1,328
Total, Medium Energy Nuclear Physics	**175,450**	**184,190**	**171,300**	**-12,890**
Heavy Ion Nuclear Physics				
Research	40,050	37,354	30,000	-7,354
Operations	187,500	193,125	186,000	-7,125
Total, Heavy Ion Nuclear Physics	**227,550**	**230,479**	**216,000**	**-14,479**
Low Energy Nuclear Physics				
Research	66,500	70,530	58,450	-12,080
Operations	29,250	30,215	36,838	+6,623
Total, Low Energy Nuclear Physics	**95,750**	**100,745**	**95,288**	**-5,457**
Nuclear Theory				
Theory Research	38,750	46,469	37,040	-9,429
Nuclear Data	8,600	8,858	7,726	-1,132
Other Project Costs	—	—	1,500	+1,500
Total, Nuclear Theory	**47,350**	**55,327**	**46,266**	**-9,061**
Isotope Development and Production for Research and Applications				
Research	11,000	9,808	12,000	+2,192
Operations	29,700	34,451	39,000	+4,549
Total, Isotopes[a]	**40,700**	**44,259**	**51,000**	**+6,741**
Subtotal, Nuclear Physics	**586,800**	**615,000**	**579,854**	**-35,146**

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

(dollars in thousands)

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Construction				
14-SC-50, Facility for Rare Isotope Beams	97,200	75,000	40,000	-35,000
20-SC-51, U.S. Stable Isotope Production and Research Center	—	—	5,000	+5,000
Total, Nuclear Physics	**684,000**	**690,000**	**624,854**	**-65,146**

SBIR/STTR Funding:

- FY 2018 Enacted: SBIR $16,875,000 and STTR $2,373,000
- FY 2019 Enacted: SBIR $17,500,000 and STTR $2,461,000
- FY 2020 Request: SBIR $16,336,000 and STTR $2,297,000

Nuclear Physics
Explanation of Major Changes

	(dollars in thousands) FY 2020 Request vs FY 2019 Enacted
Medium Energy Nuclear Physics	**-12,890**
The Request supports the highest priority research in medium energy nuclear physics at universities and national laboratories. 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 taking and analysis, cryogenics plant, scientific researchers on site and at other laboratories and universities, on site accelerator scientists and technicians, and operation of the recently upgraded CEBAF accelerator to support 1,020 operating hours. The Request provides support for experimental activities that will utilize some of the newly upgraded experimental halls to implement the 12 GeV CEBAF physics program; 12 GeV researchers from national laboratories and universities implement, commission, and operate the highest priority new experiments at CEBAF. The Request fully funds the End Station Refrigerator GPP to mitigate substantial risk to CEBAF operation. The Request supports 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. The Request initiates support for the MOLLER MIE, which will measure the parity-violating asymmetry in electron-electron scattering at CEBAF. Funding continues for the highest priority accelerator R&D to support transformative accelerator science activities that significantly advance the state-of-the-art and activities to reduce risk in next-generations NP machines and improve performance of operating machines.	
Heavy Ion Nuclear Physics	**-14,479**
The Request supports the highest priority research in heavy ion nuclear physics at universities and national laboratories. It 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 1,500 hour run, high priority core competencies, and experimental activities to prepare scientific instrumentation and infrastructure for the scientific program. The FY 2020 run will continue the high precision scan of the QCD phase diagram and search for the critical point by looking for signs of critical phenomena in event-by-event fluctuations. The Request supports the highest priority RHIC facility investments in capital equipment and accelerator improvement projects to maintain viability of the facility. Funding decreases for the ongoing sPHENIX MIE which will study high rate jets of particles at RHIC. Support for the U.S. participation in the complementary LHC program continues although annual U.S. commitments and fees for participation and computing are deferred until the following year, which may impact U.S. participation. Funding continues for the highest priority accelerator R&D to support transformative accelerator science activities that significantly advance the state-of-the-art and activities to reduce risk in next-generations NP machines and improve performance of operating machines.	

	(dollars in thousands) FY 2020 Request vs FY 2019 Enacted
Low Energy Nuclear Physics	**-5,457**

The Request supports the highest priority university and laboratory nuclear structure and nuclear astrophysics efforts at the ATLAS facility, which will operate for 2,090 hours. The Request supports targeted ATLAS facility investments in accelerator and scientific instrumentation capital equipment. Funding decreases for the ongoing GRETA MIE for FRIB according to the project plan; 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. The Request initiates the compelling High Rigidity Spectrometer to exploit the fast beam capabilities at FRIB. The Request maintains operations of the 88-Inch Cyclotron at the Lawrence Berkeley National Lab (LBNL) for an in-house nuclear science program and an electronics irradiation capability for the Department of Defense and NASA. Funding maintains operations of the three experimental University Centers of Excellence, the Texas A&M Cyclotron Facility, the HIGS at the Triangle Universities Nuclear Laboratory, and the CENPA at the University of Washington. Funding for Fundamental Symmetries research supports the highest priority activities in neutrinoless double beta decay domestically and abroad to determine whether the neutrino is its own antiparticle; funding is requested for the highest priority R&D towards next-generation experiments and the initiation of a world-leading ton-scale experiment MIE to reach unprecedented sensitivities. Funding in Fundamental Symmetries also includes targeted efforts such as the Fundamental Neutron Physics Beamline at the SNS and the continued development of its flagship experiment that, the nEDM experiment, to study neutron properties and study matter/anti-matter asymmetries in the universe.

Nuclear Theory	**-9,061**

The Request supports the highest priority theory research efforts at laboratories and universities, the U.S. Nuclear Data Program, and continues specialized Lattice Quantum Chromodynamics (LQCD) computing hardware at TJNAF and participation in SCIDAC. The Request supports targeted investments in QIS and quantum computing (QC), including the highest priority 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. NP-related QIS and QC efforts have direct relevance for this area of interest in general, and can lead to advances that are important for applications in QIS and QC. The Request includes OPC funding for conceptual design and high risk R&D for the proposed Electron-Ion Collider, which recently received a strong endorsement from the National Academy of Sciences.

	(dollars in thousands) FY 2020 Request vs FY 2019 Enacted
Isotope Development and Production for Research and Applications The Request increases funding for university and laboratory research in new isotope production techniques and establishes core R&D groups at two new Isotope Program sites – ANL and MSU. The Request also initiates the FRIB Isotope Harvesting project, an accelerator improvement project at MSU, is supported to that will add isotope harvesting capabilities to the accelerator. Funding continues to support targeted efforts to produce Ac-225 and develop other promising cancer therapeutic isotopes for clinical trials and applications. Operations funding increases to effectively support mission readiness for production activities at national laboratory facilities. The Request provides a modest increase in university operations for a network of university accelerators and reactors to establish cost-effective, regional production of short-lived isotopes for research and medical applications; this includes the University of Washington cyclotron and University of Missouri Research Reactor. A modest increase provides for additional staff at the National Isotope Development Center to effectively address the significantly expanded Isotope Program product portfolio and the development of Drug Master Files for new medical isotopes. ESIPP is operated to produce research quantities of enriched stable isotopes. The Request includes increased funding to enhance activities related to the development of enriched isotopes for next generation quantum information systems and for the DOE Isotope Program participation in the coordinated SC QIS research and facility activities. The Request supports investments to increase isotope availability and production capabilities, including He-3 for cryogenics, Li-7 for reactor operations, infrastructure investments to increase processing capabilities of radioisotopes, and the development of new enriched stable isotope production capabilities for targeted isotopes.	**+6,741**
Construction Construction funding ramps down according to the baselined profile for the Facility for Rare Isotope Beams. Engineering effort and long-lead procurements begins on the new United States Stable Isotope Production and Research Center (U.S. SIPRC) to expand the nation's capabilities for expanded production capabilities.	**-30,000**
Total, Nuclear Physics	**-65,146**

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

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

Program Accomplishments
Science Under Pressure. New results from scattering electrons off quarks inside nuclei at the Continuous Electron Beam Accelerator Facility (CEBAF) indicate that the average peak pressure experienced by quarks near the center of protons is about 10^{35} pascals, or about 10 times greater than the pressure estimated inside the densest neutron stars. At the very center of a proton, the pressure experienced by quarks is strongly repulsive. At greater distances from the center, it is attractive. These results will allow exploration of the fundamental gravitational properties of protons, neutrons and nuclei. They will also help with the continuing quest by modern physics to gain a microscopic understanding of how quarks are confined within the protons and neutrons forming the nucleus of every atom and the visible mass of the universe. The recently commissioned 12 GeV CEBAF, which is now delivering beams to four experimental halls simultaneously, will enable a watershed of new scientific insights including a search for previously unobserved exotic mesons, a sensitive search for new physics, new understanding of the origin of the proton's spin, and pioneering tomographic imaging of the proton.

Nuclear and Atomic Worlds in Collision Impact the Synthesis of Heavy Elements. Within the atom's microsphere, the protons and neutrons in the nucleus and its much larger surrounding electron cloud, don't normally interact much. Held together at a distance by mutual Coulomb attraction they are almost always non-interacting. Rarely however, via a process called "internal conversion" these two subatomic worlds collide and an excited nucleus emits an energetic electron. This process is known and has been observed; since 1976 however, the question has been whether the inverse process is also possible. That question has now been answered by scientists working at Argonne National Lab. They made the first observation of a free electron captured into an atomic vacancy resulting in a nucleus being excited to a higher energy state, called nuclear excitation by electron capture (NEEC). This is particularly significant for models of how heavy elements are synthesized in violent events in the cosmos. Nuclear states called isomers produced in such cosmic furnaces can be particularly long-lived, dramatically impacting the time at which heavy nuclei are "forged". The discovery of NEEC means the density of long-lived states can be strongly depleted in favor of shorter lived nuclear states, dramatically accelerating processes by which stable heavy elements, such as gold and platinum, are produced.

A needle in a million-billion-trillion nuclear haystack. Three first-generation experiments have now confirmed that, if one has the patience to search for an entire year, less than one out of a million-billion-trillion atomic nuclei will decay via neutrino-less double beta decay. The Majorana Demonstrator (MJD), the Cryogenic Underground Observatory for Rare Events (CUORE), and the Enriched Xenon Observatory (EXO-200) all now know this is true because they searched diligently for more than a year and didn't see a signal. Neutrino-less double beta decay occurs if two neutrons in a nucleus each decay into a proton and an electron with no emission of neutrinos. The observation of neutrino-less double beta decay would be a paradigm-changing discovery indicating that the neutrino is its own anti-particle—a discovery with profound implications for the nature of the neutrino, and for resolving the mystery of why the neutrino mass is much, much smaller than the other leptons and the quarks. Ultimately a limit for detection or exclusion of neutrino-less double beta decay 10-100 times more stringent is the target of future research and next-generation proposed detectors.

An unanticipated new window into the workings of QCD. RHIC has the exceptional advantage of being a dedicated scientific facility for "chasing down" scientific clues about one of nature's most guarded mysteries—how QCD, the theory of the strong force, works. To advance understanding in this area, in 2018, RHIC accelerated beams of isobars –Ruthenium-96 (Ru-96) and Zirconium-96 (Zr-96) -- nuclei with the same total number of protons and neutrons but with different numbers of protons and neutrons individually. In this case, the four additional protons in Ru-96 compared to Zr-96 were critical. That's because Ru-96 nuclei colliding at nearly the speed of light should generate a significantly larger instantaneous magnetic field than collisions of Zr-96. If current theory conjecture is correct about the origin of parity violating charged particle correlations previously observed in such collisions at RHIC, the differing magnetic fields for the two isobars should result in a 15-20% difference in their magnitude. Confirmation of this hypothesis would provide groundbreaking new access to the microscopic workings of QCD. Enriched Ru-96 was not available anywhere in the world, so the RHIC team needed an assist from ORNL scientists in the DOE Isotope Program who also had to accomplish something extraordinary to help out: develop new capability for electromagnetic separation of isotopes. This challenging technical development required an intense effort, but knowing that RHIC had a small window in its experimental program to accomplish the isobar measurement, the ORNL isotope team commissioned the new enrichment capability and produced the rare Ru-96 on time. Results indicating whether the newly observed phenomena at RHIC constitute another important discovery should be available in about a year.

Enabling life-saving Research through Availability of Actinium-225. One of the most breathtaking developments in cancer treatment is recent success in trials which treat metastasized late-stage prostate cancer with the use of the alpha-emitting isotope Ac-225. Ac-225 is one of a number of alpha emitting isotopes, which if delivered to the site of a cancer cell, will irradiate a microscopic volume of tissue in its immediate vicinity, leaving healthy tissue farther away unharmed. Trial results have been stunningly successful[a]. Beyond the efficacy of this approach however, the key to making treatment options viable is sufficient quantities of Ac-225 to fully support clinical trials and therapy. The DOE Isotope Program formed a Tri-Laboratory Collaboration of scientists at Brookhaven, Los Alamos, and Oak Ridge National Laboratories with unique facilities and expertise to develop large-scale production capacity of Ac-225. The Tri-Laboratory Collaboration is now routinely producing up to 50 millicuries (mCi) batches of Ac-225 twice a month for clinical trials and will soon be capable of routine bi-weekly production runs of 100 mCi. Ultimately, the effort will be scaled up to bi-weekly production runs of at least 1,000 mCi --the equivalent of the current annual U.S. production of Ac-225 based on harvesting from the natural decay of legacy thorium-229.

Terra Incognita Near the Island of Stability for Super-heavy Nuclei. Oganesson (Og) is one of four new super-heavy elements confirmed by the International Union of Pure and Applied Physics and added to the periodic table of the elements and the chart of nuclides. Og has an atomic number of 118 (the heaviest element ever confirmed), and a half-life of less than a

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[a] J. Nucl. Med., 2016; 57 (12); 1941 DOI: 10.2967/jnumed.116.178673 C. Kratochwil

millisecond. Discovered indirectly by nuclear physicists via observation of characteristic alpha particle decay chains, the chemical properties and electron structure of Og and its companions (Nihonium, Moscovium, Tennessine) are currently conjecture. To help unfold this mystery, using state-of-the art atomic and nuclear models and advanced computational tools, an international team of researchers, supported in part by the Office of Nuclear Physics, has calculated the electronic and nucleonic shell structure of Og. Formerly speculated to be a gas under normal conditions, Og is now predicted to be a metal at room temperature. Surprisingly, it may also be significantly reactive, unlike all the other elements of the group it identifies with (the noble gases) in the periodic table. These results are a significant contribution to the voyage of discovery to determine the properties of Og and its companion super-heavy nuclei.

A New Attack on the Problem of the Neutrino Mass. Even though neutrinos hold a special place in the workings of the universe, one of their most basic properties, their mass, is unknown. The international KATRIN experiment in Germany, in which U.S. nuclear physicists play leading scientific and technical roles, recently achieved a major milestone with the introduction of tritium to the experimental apparatus to begin first measurements of the electrons from tritium decay. If the energy of such electrons is measured precisely, the mass of neutrinos from tritium decay can be reconstructed via conservation of momentum and energy. The KATRIN experiment is the largest and most precise instrument of its type so far, with a goal of setting a limit on the neutrino mass significantly smaller than the currently available model dependent limits. With the start of operations of the experiment, the stage is set for the eagerly awaited data to achieve its experimental goals.

Thin Skinned Neutron Stars in the Cosmos. The first detection of a binary neutron star merger by the LIGO-Virgo collaboration is providing fundamentally new insights into the astrophysical site for the rapid-neutron capture process ("r-process") responsible for the creation of most heavy elements in the Universe. Theorists supported by the Office of Nuclear Physics confronted the predictions of realistic models of the equation of state (EOS) of matter against experimental data extracted from the LIGO gravitational-wave data. Given the sensitivity of the gravitational-wave signal to the underlying EOS, constraints can be placed on the neutron star radius. Based on these constraints, models that predict large stellar radii can be ruled out and an upper limit of about 0.25 femtometers is inferred for the neutron-skin thickness.

Nuclear Physics
Medium Energy Nuclear Physics

Description

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

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

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

The Medium Energy Nuclear Physics subprogram supports research at and operation of the subprogram's primary research facility, CEBAF at TJNAF, as well as the spin physics research that is carried out using RHIC at BNL. The subprogram has provided support for spin physics research at RHIC, 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 polarized electrons to make 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. 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 will secure continued U.S. world leadership in this area of physics. The upgrade construction project was successfully completed on cost and schedule in 2017, and the highly anticipated science program was launched in FY 2018. Some of the science goals of the 12 GeV experimental program include the search for exotic new quark anti-quark particles to advance our understanding of the strong force, evidence of new physics from sensitive searches for violations of nature's fundamental symmetries, and a microscopic understanding in the 12 GeV energy regime of the internal structure of the proton, including the origin of its spin, and how this structure is modified when the proton is inside a nucleus. Next generation instrumentation to fully exploit the capabilities of the 12 GeV CEBAF are implemented, including the MOLLER MIE initiated in FY 2020, which will measure the parity-violating asymmetry in electron-electron scattering at CEBAF. Research at RHIC using colliding beams of spin-polarized protons, a capability unique to RHIC, will provide information on the origin of 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 HIGS at TUNL, Fermilab, Europe, and elsewhere. The Research and Engineering Center of the Massachusetts Institute of Technology (MIT) has specialized infrastructure used to develop and fabricate advanced instrumentation and accelerator equipment.

Since the 2002 LRP for Nuclear Science, 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 following the completion of FRIB." Most recently a National Academy of Science 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 sub-programs are actively engaged in the development of the scientific agenda, conceptual design of the facility, accelerator R&D and development of scientific instrumentation R&D related to a proposed EIC.

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

Research
The Medium Energy Research subprogram supports a focused effort of medium energy research groups at TJNAF, BNL, ANL, the Los Alamos National Laboratory (LANL), and LBNL to carry out the highest priority research programs and experiments at CEBAF, RHIC, and elsewhere. Scientists participate in the development and implementation of targeted advanced instrumentation, including state-of-the-art detectors for experiments that may also have application in areas such as medical imaging instrumentation and homeland security. TJNAF staff research efforts focus on the 12 GeV experimental program, including implementation of select experiments, acquisition of data, and data analysis at select CEBAF experimental halls (Halls A, B, C, and D) and RHIC. Scientists conduct targeted research to advance knowledge and to identify and develop the science opportunities and goals for next generation instrumentation and facilities. 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. Scientists at TJNAF and elsewhere participate in the initiation of the MOLLER MIE, which will measure the parity-violating asymmetry in electron-electron scattering.

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

Accelerator R&D research proposals for short and mid-term accelerator R&D from universities and laboratories specific to improving operations of current NP facilities or developing new NP facilities are evaluated by peer review through a single competition for funding that is included under the Heavy Ion and Medium Energy subprograms. The Request prioritizes support for transformative accelerator science activities that significantly advance the state-of-the-art. Researchers participate in the conceptual design of the EIC and development of scientific and experimental plans for the proposed machine.

Operations
The science user community, including a strong international component, uses CEBAF's polarized electron beam capabilities to study the contributions of quarks and gluons to the properties of hadrons. The subprogram provides Accelerator Operations funding for a team of accelerator physicists at TJNAF that operate CEBAF, as well as for power costs of operations and maintenance of the 12 GeV CEBAF. The Request provides investments in the highest priority accelerator improvements aimed at addressing CEBAF reliability and the highest priority capital equipment for research and facility instrumentation. Included in the Request is a one-time increase to GPP funding to fully fund a critically needed replacement of the End Station Refrigerator to mitigate end-of-life risk of current equipment and provide required additional capacity for future experiments. Support is provided for targeted efforts in developing advances in superconducting radiofrequency (SRF) technology relevant to improving operations of the existing machine. The core competency in SRF technology plays a crucial

role in many DOE projects and facilities outside of nuclear physics [such as the Basic Energy Sciences project Linac Coherent Light Source (LCLS II)] and has broad applications in medicine and homeland security. For example, SRF R&D at TJNAF has led to improved land-mine detection techniques and carbon nanotube and nano-structure manufacturing techniques for constructing super-lightweight composites such as aircraft fuselages. TJNAF also has a core competency in cryogenics and has developed award-winning techniques that have led to more cost-effective operations at TJNAF and several other SC facilities; their cryogenics expertise is being applied to the FRIB project and LCLS-II. TJNAF accelerator physicists help train the next generation of accelerator physicists, enabled in part by a close partnership with nearby universities and other institutions with accelerator physics expertise. Accelerator scientists participate in the development of the EIC conceptual design. The subprogram provides focused 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. Four experimental halls, increased from three prior to the 12 GeV upgrade, are now capable of providing new and enhanced capabilities for scientists world-wide.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Medium Energy Nuclear Physics	**$184,190,000**	**$171,300,000**	**-$12,890,000**
Research	$43,286,000	$35,500,000	-$7,786,000
The FY 2019 Enacted budget supports scientific participation in the 12 GeV experimental program at CEBAF. Science goals include the search for exotic new quark/anti-quark particles, sensitive searches for violations of nature's fundamental symmetries, and a detailed microscopic understanding of the internal structure of the proton. This includes support for scientific workforce resident at TJNAF and outside universities and national laboratories that plan the scientific program; develop, implement and maintain scientific instrumentation; participate in the experimental runs to acquire data; analyze data and publish experimental results; and train students in nuclear science. Analysis of prior RHIC polarized proton beam data to learn more about the origin of the proton's spin, and support for short and mid-term accelerator R&D, continues.		The FY 2020 Request provides support for key scientists participating in the highest priority experiments taking data in select experimental halls at the CEBAF 12 GeV program. This includes support for critical scientific workforce resident at TJNAF and outside universities and national laboratories that plan the scientific program; develop, implement and maintain scientific instrumentation; participate in the experimental runs to acquire data; analyze data and publish experimental results; and train students in nuclear science. The Request continues targeted analysis of RHIC polarized proton beam data to learn more about the origin of the proton's spin and focused support for high priority accelerator R&D. The MOLLER MIE, which will measure the parity-violating asymmetry in electron-electron scattering, is initiated.	Decreased research funding supports high priority research activities and critical scientific workforce at universities and national laboratories conducting research at CEBAF, RHIC and other facilities. Decreased research funding supports high priority efforts in accelerator R&D activities that support transformational accelerator science and aimed at reducing risk and improving performance. The Request initiates the MOLLER MIE.
Operations	$117,390,000	$114,500,000	-$2,890,000
Operations of the newly upgraded CEBAF facility will support the continuation of the high priority 12 GeV science program, following the successful completion of the project in 2017. Funding supports 4,080 operational hours of running for research, tuning, and beam studies. Experiments in multiple halls will be operated for data taking.		Operations of the newly upgraded CEBAF facility will support the continuation of the highest priority experiments in the 12 GeV science program. Funding will support 1,020 operational hours for research, tuning, and beam studies. The Request provides support to maintain critical core competencies that will increase the reliability of the CEBAF and conduct experiments in select halls. The Request supports targeted facility capital equipment, accelerator	The Request includes a one-time increase to GPP funding to fully fund a critical replacement End Station Refrigerator to mitigate end-of-life risk of current equipment and provide added capacity for future experiments.

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
	improvements, and the End Station Refrigerator GPP project. Accelerator scientists will participate in the highest priority accelerator R&D.	
Other Research $3,553,000	$2,667,000	-$886,000
Funding is provided for DOE and Office of Science requirements.	Funding is provided for DOE and Office of Science requirements.	Funding is provided for DOE and Office of Science central IT and working capital requirements.
SBIR/STTR $19,961,000	$18,633,000	-$1,328,000
Funding will be provided in accordance with the Small Business Innovation Development Act and subsequent related legislation.	Funding will be provided in accordance with the Small Business Innovation Development Act and subsequent related legislation.	The SBIR/STTR funding will be consistent with the NP total budget.

Nuclear Physics
Heavy Ion Nuclear Physics

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

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

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

The RHIC facility places heavy ion research at the frontier of discovery in nuclear physics. The RHIC facility 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 enables a groundbreaking science program extending into the next decade to answer outstanding questions about this exotic form of matter and whether a critical point exists in the phase diagram of nuclear matter. Within available resources, scientists participate in instrumentation upgrades, such as enhancements to the capabilities of the STAR detector, and an upgrade of the PHENIX detector to sPHENIX with funds previously used to operate the PHENIX detector. Accelerator physicists participate in short and mid-term accelerator R&D at RHIC in critical areas that may include the cooling of high-energy hadron beams, high intensity polarized electron sources, and high-energy, high-current energy recovery linear accelerators. The RHIC facility is typically used by about 1,200 DOE, NSF, and foreign agency-supported researchers annually.

Since the 2002 LRP for Nuclear Science, 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 following the completion of FRIB." Most recently a National Academy of Science 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.[a] Scientists and accelerator physicists from both the Medium Energy and Heavy Ion sub-programs are actively engaged in the development of the scientific agenda, conceptual design of the facility, accelerator R&D and development of scientific instrumentation R&D related to a proposed EIC.

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

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 infant 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 comparing these results to the results at RHIC has 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

The subprogram supports key heavy ion research groups at BNL, LBNL, LANL, and the Oak Ridge National Laboratory (ORNL) to participate in the highest priority efforts at RHIC and the LHC. U.S. commitments to the LHC "common funds", fees to support individual U.S. scientist participation in the LHC program and the use of LHC computing capabilities, are deferred to the following year. In FY 2020, university workforce will also be focused on the highest priority efforts at RHIC and the LHC.

The university and national laboratory research groups provide focused personnel and graduate students for taking data within the RHIC heavy ion program; analyzing data; publishing results; conducting R&D of next-generation detectors; developing and implementing scientific equipment; and planning for future experiments. BNL and LBNL provide computing infrastructure for petabyte-scale data analysis and state-of-the-art facilities for detector and instrument development.

Accelerator R&D research proposals for short and mid-term accelerator R&D from universities and laboratories specific to improving operations of current NP facilities or developing new NP facilities are evaluated by peer review through a single competition for funding that is included under the Heavy Ion and Medium Energy subprograms. Transformative accelerator science activities that significantly advance the state-of-the-art are a priority in the Request. Researchers participate in the conceptual design of the EIC and development of scientific and experimental plans for the proposed machine in FY 2020.

Operations

The Heavy Ion subprogram provides decreased support for the operations and power costs of the RHIC accelerator complex at BNL. In FY 2020, the Request supports the highest priority capital equipment and accelerator improvement projects at RHIC. The accelerator complex includes the Electron Beam Ion Source (EBIS), Booster, and the Alternating Gradient Synchrotron (AGS) accelerators that together serve as the injector for RHIC. Staff provide key experimental support to the facility, including the development, implementation, and commissioning of scientific equipment associated with the RHIC program. In FY 2020, the only detector operating at RHIC is STAR; PHENIX operations funding is redirected to continue to upgrade the PHENIX detector to the sPHENIX MIE. sPHENIX will enable scientists to study how the near-perfect QGP liquid, which has the lowest shear viscosity ever observed arises from the strongly interacting quarks and gluons from which it is formed. Accelerator Improvement Projects in prior years have focused on the LEReC Project, installed in FY 2018, which cools low energy heavy ion beams with bunched electron beam and is projected to increase the luminosity by up to another factor of ten.

Through operations of the RHIC complex, important core competencies have been nurtured in accelerator physics techniques to improve RHIC performance and support the NP mission. These core competencies provide collateral benefits to applications in industry, medicine, homeland security, and other scientific projects outside of NP. RHIC accelerator physicists are providing leadership and expertise to reduce technical risk of relevance to a possible next-generation collider, including beam cooling techniques and energy recovery linacs; they continue to participate in EIC-specific R&D and the development of a conceptual design for the EIC accelerator physicists also play an important role in the training of next generation accelerator physicists, with support of graduate students and post-doctoral associates.

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

Nuclear Physics
Heavy Ion Nuclear Physics

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Heavy Ion Nuclear Physics	**$230,479,000**	**$216,000,000**	**-$14,479,000**
Research	$37,354,000	$30,000,000	-$7,354,000
Researchers participate in the analysis and collection of data from RHIC to explore new phenomena in quark-gluon plasma formation, with a particular search for signs of critical phenomena in event-by-event fluctuations that could reveal the critical point in the QCD Phase Diagram. Modest scientific efforts initiate the sPHENIX MIE for the study of high rate particle jets. This includes support for scientific workforce resident at RHIC and outside universities and national laboratories that plan the scientific program; develop, fabricate, implement and maintain scientific instrumentation; participate in the experimental runs to acquire data; analyze data and publish experimental results; and train students in nuclear science. U.S. scientists play a leadership role in the heavy ion efforts at the international ALICE, CMS, and ATLAS LHC experiments, and provide the required funding to the LHC for U.S. commitments for management and operating costs, computing, and contributions towards upgrades of the ALICE detector. Mid- and short-term accelerator R&D relevant to NP programmatic needs are supported.		Critical researchers will participate in the highest priority analysis and collection of data from RHIC to explore new phenomena in quark-gluon plasma formation, with a particular search for signs of critical phenomena in event-by-event fluctuations that could reveal the critical point in the QCD Phase Diagram. The Request provides targeted support for scientific workforce resident at RHIC and outside universities and national laboratories to develop, fabricate, implement and maintain scientific instrumentation; participate in select experimental runs to acquire data; analyze data and publish experimental results; develop scientific plans and instrumentation for a proposed EIC; and train students in nuclear science. The Request also provides support to enable scientists to continue to implement the sPHENIX MIE for the study of high rate particle jets. U.S. scientists participate in the highest priority heavy ion efforts at the international ALICE, CMS, and ATLAS LHC experiments. In addition, the Request supports the highest priority accelerator R&D relevant to NP programmatic needs.	Decreased research funding supports critical workforce at universities and national laboratories associated with implementing the high priority RHIC science program. U.S. participation in the LHC continues, but commitments to the LHC "common funds", fees to support individual U.S. scientist participation in the LHC program and the use of LHC computing capabilities, are deferred.

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Operations $193,125,000	$186,000,000	-$7,125,000
RHIC will operate for 3,290 hours and will focus on the beam energy scan with the newly implemented Low Energy electron Cooling to increase luminosity of low energy beams. Funding supports the RHIC accelerator complex (four different particle accelerators not including the RHIC collider rings that are 2.4 miles in circumference), 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, accelerator scientists, engineers, and technicians, and RHIC operations staff. High priority facility specific accelerator R&D will continue.	RHIC will operate for 1,500 hours and will focus on the beam energy scan with the newly implemented Low Energy Electron Cooling to increase luminosity of low energy beams. Funding supports the RHIC accelerator complex, including mission readiness and development of the experimental halls and instrumentation, mission readiness of the suite of accelerators, all power and consumables of the site, cryogenics plant, the highest priority facility and instrumentation capital equipment, the highest priority accelerator improvement projects, and the key computing capabilities for data taking and analysis. Support is provided to maintain critical core competencies and essential accelerator scientists, engineers, and technicians, and RHIC operations staff. Limited operations funding is redirected to the sPHENIX MIE which will study high rate particle jets; the impact to the sPHENIX cost and schedule will be assessed upon a FY 2020 Appropriation. Accelerator scientists participate in the highest priority accelerator R&D.	The Request provides limited support for facility and instrumentation capital equipment and Accelerator Improvement Projects to maintain the viability of the machine. Adjustment of support below project plans enables the continuation of the sPHENIX MIE while optimizing operations within available funds.

Nuclear Physics
Low Energy Nuclear Physics

Description

The Low Energy Nuclear Physics subprogram focuses on answering the overarching questions associated with Nuclei and Nuclear Astrophysics and Fundamental Symmetries that can be probed by studying neutrons and nuclei.
Questions associated with Nuclei 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 is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?

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

Questions addressed in the area of Fundamental Symmetries that can be probed by studying neutrons and nuclei include:

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

The Fundamental Symmetries portfolio currently addresses these questions through precision studies using neutron beams and decays of nuclei, including neutrinoless double-beta decay. U.S. scientists are world leaders in the global research effort aimed at neutrino science and NP is the steward of neutrinoless double beta decay in the Office of Science. In partnership with the NSF, NP has invested in past, current and future neutrino experiments both domestically and overseas, playing critical roles in international experiments that depend on U.S. leadership for their ultimate success (CUORE, KATRIN), and R&D of candidate technologies for next–generation experiments, including germanium (MJD and LEGEND), xenon (nEXO) and tellurium (CUPID). In partnership with the NSF, NP initiated support for the LEGEND-200 prototype in FY 2019. The NSAC 2015 LRP has as its second recommendation “the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.” Neutrino-less double beta decay can only occur if neutrinos are their own anti-particles and the observation of “lepton number violation” in such events would have profound, game changing consequences for the present understanding of the physical universe. The Request includes funding for the initiation of a Ton-Scale Neutrinoless Double Beta Decay (NLDBD) MIE, which is expected to provide unprecedented resolution for the detection of the rare process; the MIE received CD-0, Approve Mission Need, in November 2018.

Beams of cold and ultracold neutrons at the SNS are used to study fundamental properties of neutrons, and an experiment for this beamline to measure the electric dipole moment of the neutron, which could shed light on the asymmetry of matter versus antimatter in the universe, is on the path towards becoming the flagship experiment at this beamline. Precision studies to observe or set a limit on violation of time-reversal invariance—the principle that the physical laws should not change if the direction of time is reversed—in nucleonic, nuclear, and atomic systems investigate fundamental questions in nuclear physics, astrophysics, and cosmology.

The ATLAS scientific user facility at ANL is the DOE-supported facility providing research opportunities in Nuclear Structure and Nuclear Astrophysics, serving a combined international community of over 400 scientists. 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 nuclei for experimental studies of nuclear properties under extreme conditions and reactions of interest to nuclear astrophysics. ATLAS also provides some capabilities in radioactive or rare isotope beams with the Californium Rare Ion Breeder Upgrade (CARIBU) ion source. The facility continues to provide increasingly higher intensity stable beams and improved quality radioactive beams with modest accelerator improvements. Technologically cutting-edge and unique instrumentation are a hallmark at the facility, and the ATLAS Facility continues to be significantly oversubscribed by the user community. In addition to its world-class, standalone scientific program, ATLAS is also an essential training ground for scientists and students as they prepare for the FRIB research program. The ATLAS facility nurtures a core competency in accelerator science with superconducting radio frequency cavities for heavy ions that are relevant to the next generation of high-performance proton and heavy ion linacs. This competency is important to the 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.

There are two university Centers of Excellence within the Low Energy subprogram with specific goals and unique physics programs: the Cyclotron Institute at TAMU and accelerator facilities at the TUNL at Duke University. A third university center, CENPA at the University of Washington, provides unique expertise and capabilities for instrumentation development. NP also supports operations of the LBNL 88-Inch Cyclotron to provide beams for a small in-house nuclear science program focused on studying the properties of newly discovered elements on the periodic table, and unique testing capabilities in materials irradiation important for external users and other critical missions, such as the Department of Defense and NASA.

The FRIB, under construction at Michigan State University (MSU), will advance understanding of rare nuclear isotopes and the evolution of the cosmos by providing beams of rare isotopes with neutron and proton numbers far from those of stable nuclei in order to test the limits of nuclear existence. Support for FRIB operations retains critical operations staff as accelerator components on the project are completed and efforts transition to operations. The Gamma-Ray Energy Tracking Array (GRETA) MIE is one of the primary tools that the nuclear science community has identified to leverage the capabilities of FRIB. GRETA will have ten times the gamma-ray resolving power of current generation detectors for the vast majority of experiments, and up to a factor of 100 for those requiring multiple gamma-ray correlations. GRETA's unprecedented combination of full coverage with high efficiency, and excellent energy and position resolution, will extend the reach of FRIB's ability to study the nuclear landscape, provide new opportunities to discover and characterize key nuclei for electric dipole moment searches, and open new areas of study in nuclear astrophysics. The High Rigidity Spectrometer (HRS) at FRIB specifically exploits the fast beam capabilities of this powerful accelerator. The HRS will enable the most sensitive experiments across the entire chart of nuclei, thereby enabling experiments with the most neutron-rich nuclei available at FRIB.

<u>Research</u>

The subprogram will support the highest priority efforts of Low Energy research groups at ANL, BNL, LBNL, LANL, LLNL, ORNL, and PNNL. About half of the scientists conduct nuclear structure and astrophysics research primarily using specialized instrumentation at the ATLAS scientific user facility. The Request provides limited support of the GRETA MIE. Essential scientists are supported to participate in the initiation of the HRS MIE to exploit the fast beam capabilities of FRIB, and to conduct research in fundamental symmetries, including experiments at the Fundamental Neutron Physics Beamline (FNPB) at the SNS. Focused R&D continues towards an experiment to measure the electric dipole moment of the neutron, which could shed light on the asymmetry of matter versus antimatter in the universe. Currently operating double beta-decay experiments continue to acquire data, such as the Cryogenic Underground Observatory for Rare Events (CUORE) experiment at Gran Sasso Laboratory in Italy and the Majorana Demonstrator R&D effort at the Sanford Underground Research Facility in Lead, South Dakota. The highest priority R&D aimed at a ton-scale neutrinoless double beta decay experiment continues with nEXO and the provision of scientific and technical leadership to LEGEND-200. U.S. researchers lead the initiation of an international ton-scale NLDBD MIE. Scientists participate in the operations of the Karlsruhe Tritium Neutrino (KATRIN) experiment at the Karlsruhe Institute of Technology in Karlsruhe, Germany to provide a measurement of the neutrino mass. The Request provides support to the university Centers of Excellence at TUNL, CENPA and TAMU for the conduct of experiments at these niche facilities. Funding to nurture an FRIB-specific research community is deferred in the short term.

Operations

ATLAS provides highly reliable and cost-effective stable and selected radioactive beams and specialized instrumentation for scientists to conduct research on nuclear structure and nuclear astrophysics. In FY 2020, the Low Energy subprogram provides decreased support for the operations and power costs of the ATLAS. The subprogram provides decreased support for high priority accelerator and scientific instrumentation capital equipment, high priority accelerator improvement projects and experimental support of ATLAS. The facility complexity has been increasing, with the addition of the Electron Beam Ion Source (EBIS), the cutting edge CARIBU radioactive beam system for accelerated radioactive ion beams, the in-flight radioactive ion separator to increase the intensity of radioactive beams, and a gas filled analyzer.

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

The Request includes funding to support partial FRIB operations and retain the most critical operations staff as accelerator components are completed on the project and efforts begin to transition to operations. Staff commission accelerator components and perform system tests. The Request also provides support to maintain operations support of the 88-Inch Cyclotron for an in-house nuclear physics program.

Nuclear Physics
Low Energy Nuclear Physics

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Low Energy Nuclear Physics	**$100,745,000**	**$95,288,000**	**-$5,457,000**
Research	$70,530,000	$58,450,000	-$12,080,000
University and laboratory nuclear structure and nuclear astrophysics efforts are focused on research at ATLAS, the world's premiere stable beam facility, as well as development of the FRIB scientific program. Research and operations continue at the unique university-based Centers of Excellence. Research continues with the Majorana Demonstrator and nEXO to consider performance of different technologies in neutrinoless double beta decay experiments; research is initiated, in partnership with the NSF, for the LEGEND-200 experiment. U.S. participation in the operations of the international KATRIN and CUORE experiments continues, as does ongoing R&D at the FNPB on the feasibility of setting a world leading limit on the electric dipole moment of the neutron. The GRETA MIE is supported according to the planned profile.		The FY 2020 Request supports the highest priority university and laboratory nuclear structure and nuclear astrophysics efforts at ATLAS, the world's premiere stable beam facility, and development of the FRIB scientific program. Research support to ramp up funding for FRIB scientific personnel is deferred. Research continues at the unique university-based Centers of Excellence at TUNL, CENPA and TAMU. The Majorana Demonstrator, LEGEND-200 and nEXO continue their highest priority efforts. The Request initiates a ton-scale NLDBD MIE. U.S. participation in the operations of the international KATRIN and CUORE experiments continue. The Request will provide support for the GRETA MIE below its planned profile and initiates the HRS MIE for FRIB; the impact to the GRETA cost and schedule will be assessed upon a FY 2020 Appropriation.	The Request supports the highest priority efforts and essential workforce at universities and national laboratories associated with implementing experiments at ATLAS. Reduced funding will continue to enable progress on the GRETA MIE, and offsets initiation of the HRS for FRIB and the Ton-Scale NLDBD MIE.
Operations	$30,215,000	$36,838,000	+$6,623,000
The FY 2019 Enacted budget supports the operation of ATLAS to address the high demand for ATLAS beam time, which continues to exceed availability. ATLAS funding at this cost-effective facility will support 6,400 hours of beam time. Funding is also provided to ramp up the operations activities for FRIB according to plan.		The FY 2020 Request supports operation of ATLAS to partially address the high demand for ATLAS beam time, which continues to far exceed availability. ATLAS funding at this cost-effective facility will support 2,090 hours of beam time, maintenance, and the highest priority accelerator improvement projects and capital equipment for the facility and scientific instrumentation. Funding maintains operations of the 88" Cyclotron and to partially ramp up the operations activities for FRIB relative to planned levels.	Operations support for FRIB is increased but remains below the planned level. Funding supports reduced beam hours for experiments at ATLAS and reduced investments in capital equipment efforts and accelerator improvement projects.

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. Nuclear Theory addresses all three of NP's scientific thrusts. One major theme of theoretical research is the development of an understanding of the mechanisms and effects of quark confinement and deconfinement. A quantitative description of these phenomena through QCD is one of this subprogram's greatest intellectual challenges. New theoretical and computational tools are also being developed to describe nuclear many-body phenomena; these approaches will likely also see important applications in condensed matter physics and in other areas of the physical sciences. Another major research area is nuclear astrophysics, which includes efforts to understand the origins of the elements and the consequences that neutrino masses have for nuclear astrophysics.

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

The U.S. Nuclear Data Program (USNDP) provides current, accurate, and authoritative data for workers in pure 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 three million retrievals of nuclear data annually. The USNDP also addresses important gaps in nuclear data through targeted experiments and the development and use of theoretical models. The program involves the combined efforts of approximately 50 nuclear scientists at 10 national laboratories and universities, and is managed by the National Nuclear Data Center (NNDC) at BNL. The USNDP provides evaluated cross-section and decay data relevant to a broad suite of Federal missions and topics. USNDP also supports targeted experimental efforts on opportunistic measurements to address serious gaps and uncertainties in existing nuclear data archives. The NP leads an Inter-Agency working group including NNSA, DHS, NE, the DOE Isotope Program and other Federal Agencies to coordinate targeted experimental efforts on opportunistic measurements to address serious gaps and uncertainties in existing nuclear data archives.

Much of the research supported by the Nuclear Theory subprogram requires extensive access to leading-edge supercomputers. One area that has a particularly pressing demand for large, dedicated computational resources is Lattice QCD (LQCD). LQCD calculations 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 JLab.

Nuclear physicists participate in activities related to QIS and quantum computing (QC), in coordination with other SC research program offices. 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. NP-related QIS and QC efforts have direct relevance for this area of interest in general, and can lead to advances that are important for applications in QIS and QC in many fields.

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.

Since the 2002 LRP for Nuclear Science, 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 following the completion of FRIB.” Most recently a National Academy of Science 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. Other Project Costs (OPC) efforts related to the development of a Conceptual Design and high risk design-specific R&D are supported out of the Theory Subprogram.

Theory Research

The Nuclear Theory subprogram supports the highest priority research programs of nuclear theory groups at seven national laboratories (ANL, BNL, LANL, LBNL, LLNL, ORNL, and TJNAF). This research advances our fundamental understanding of nuclear physics, interpreting the results of experiments carried out under the auspices of the experimental nuclear physics program, and identifies and explores compelling new areas of research. The Request continues to support the 5-year topical collaborations initiated in FY 2016/FY 2017 within available funds to bring together theorists to address specific high-priority theoretical challenges. The ongoing topical collaborations will receive some continued support in FY 2020: the Beam Energy Scan Theory (BEST) Collaboration, the Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD) Collaboration, the Nuclear Theory for Double Beta Decay and Fundamental Symmetries Collaboration and the Fission in R-process Elements (FIRE) Collaboration. The BEST and TMD proposals are intimately related to LQCD, one of nuclear theory’s greatest intellectual challenges. BEST addresses “hot” QCD and the RHIC beam-energy scan, while TMD deals with “cold” QCD, three-dimensional hadron structure and spin physics, and looks forward in the direction of a future EIC. FIRE is jointly funded by NP and the NNSA to advance the theory of nuclear fission and explore the role of fission recycling in the creation of atomic nuclei in astrophysical environments. The subprogram supports high priority efforts on FRIB theory, which is critical to theory efforts associated with the planned FRIB scientific program in order to optimize the interpretation of the experimental results.

Efforts related to QIS and QC address the needs of the NP program and provide technological and computational advances relevant to other fields. Following exploratory QIS/QC workshops at the Institute for Nuclear Theory and at Argonne National Laboratory, as well as a QC “test-bed” simulation to demonstrate proof-of-principle use of quantum computing for scientific applications, an NSAC charge in FY 2019 will further articulate the priority areas in QIS/QC where unique opportunities exist for nuclear physics contributions. The output of that exercise will help to further elucidate priorities for targeted funding opportunities in FY 2020.

Five year SciDAC-4 awards selected in FY 2017 continue in FY 2020 with progress monitored via peer review. In addition to addressing specific problems relevant for nuclear physics research SciDAC-4 projects continue to serve as a water-shed for training scientists who can address national needs.

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

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Nuclear Theory	**$55,327,000**	**$46,266,000**	**-$9,061,000**
Theory Research	$46,469,000	$37,040,000	-$9,429,000
The FY 2019 Enacted budget supports QIS efforts, including support for QIS research and LQCD computing. Funding supports 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 research program at the planned FRIB, and ongoing and planned RHIC experiments. Funding supports the third year of support for SciDAC-4 grants and the fourth year for the theory topical collaborations initiated in FY 2016.		Funding will support the highest priority QIS efforts and LQCD computing hardware investments at JLab. Funding will support the most essential 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. Within available funding, support will be provided for the fourth year of SciDAC-4 grants and the final year of theory topical collaborations initiated in FY 2016.	The funding supports the highest priority efforts and critical workforce at universities and national laboratories associated with nuclear theory, SCIDAC and the FRIB Theory Alliance. Reduced funding supports activities in QIS/QC that are of high importance to NP and related to QIS/QC applications.
Other Project Costs	$—	$1,500,000	+$1,500,000
None.		The FY 2020 Request will provide for the first year of Other Project Costs for the Electron Ion Collider, aimed at research to reduce technical risk and the development of a conceptual design.	The Electron Ion Collider OPC support is initiated in FY 2020.

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Nuclear Data $8,858,000	$7,726,000	-$1,132,000
The FY 2019 Enacted budget supports the USNDP's efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. Funding supports a modest experimental component to address gaps in the existing nuclear data, in coordination with the interests and support of other federal agencies.	The FY 2020 Request will provide support for the highest priority USNDP efforts to collect, evaluate, and disseminate nuclear physics data for basic nuclear research and for applied nuclear technologies and their development. The FY 2020 Request would also provide funding for some critical experimental measurements to address gaps in existing nuclear data.	Funding supports the most essential Nuclear Data efforts and workforce, and allows for focused support of experimental nuclear data efforts.

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

Description

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

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

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

- actinium-225, actinium-227, tungsten-188, lutetium-177, strontium-90, and cobalt-60 for cancer therapy;
- californium-252 for well logging, homeland security, and energy security;
- germanium-68 for the development of gallium-68 radiopharmaceuticals for cancer imaging;
- berkelium-249, americium-243, plutonium-242, californium-251, and curium-248 for use as targets for discovery of new superheavy elements;
- selenium-75 for industrial radiography;
- bismuth-213, lead-212, astatine-211, copper-67, thorium-227, and radium-223 for cancer and infectious disease therapy research;
- nickel-63 for molecular sensing devices, and lithium-6 and helium-3 for neutron detectors for homeland security applications;
- lithium-7 as a coolant reagent for pressurized water nuclear power plants; and
- arsenic-73, iron-52, and zinc-65 as tracers in metabolic studies.

Stable and radioactive isotopes are vital to the missions of many Federal agencies including the NIH, NIST, the Department of Agriculture, DHS, NNSA, and DOE SC programs. NP continues to work in close collaboration with all federal organizations to develop strategic plans for isotope production and to establish effective communication to better forecast isotope needs and leverage resources. NP conducts biennial workshops, attended by representatives of all Federal agencies that require stable and radioactive isotopes, to provide a comprehensive assessment of national needs for isotope products and services, to inform priorities for investments in research for developing new isotope production and processing techniques,

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

to communicate advances in isotope production research and availability, and to communicate concerns about potential constrained supplies of important isotopes to the federal complex. The Isotope Program participates in a number of federal Working Groups and Interagency groups to promote communication, including the White House Office of Science and Technology Policy (OSTP) working group on molybdenum-99 (Mo-99), the National Science and Technology Committee Subcommittee on Critical and Strategic Mineral Supply Chains, and the Interagency Group on Helium-3, which it leads, that reports to the White House National Security Staff. NP participates in the Certified Reference Material Working Group which assures material availability for nuclear forensics applications that support national security missions and also the Nuclear Regulatory Commission Committee on Alternatives to Sealed Sources. As a service, the Isotope Program collects demand and usage information on helium-4 from the federal complex and provides it to the Bureau of Land Management (BLM) so that BLM can optimize their plans for the helium-4 Federal Reserve.

The DOE Isotope Program also invests in the nation's future nuclear chemistry and biomedical researchers through support for the Nuclear Chemistry Summer School (NCSS) program. The NCSS, jointly supported with the Office of Basic Energy Sciences program, consists of an intensive six-week program of formal accredited lectures on the fundamentals of nuclear science, radiochemistry, and their applications in related fields, as well as laboratory practicums focusing on state-of-the-art instrumentation and technology used routinely in basic and applied nuclear science.

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

The mission of the Isotope Program is facilitated by the National Isotope Development Center (NIDC), which is a virtual center that interfaces with the user community and manages the coordination of isotope production across the facilities and business operations involved in the production, sale, and distribution of isotopes. The NIDC includes the Isotope Business Office, which is located at ORNL.

Research

The subprogram supports innovative research to develop new or improved production or separation techniques for high priority isotopes in short supply. Research investments tackle challenges in the efficiency of producing critical isotopes, and develop advanced production methods for isotopes of interest to federal agencies and other stakeholders, when no production route is in existence, enabling new applications and research. The research activity has two primary components. One is support of R&D via competitive funding opportunity announcements open to both universities and laboratories. The other is provision of core R&D funding to national laboratories and universities that possess unique facilities and technical expertise that directly support the mission of the DOE Isotope Program. In both components, peer review is used to assess the quality of the research being performed and its relevance for assuring availability of isotopes that are in short supply and needed for research and applications important to the Nation's science and industry. There is also an emphasis in the R&D program on providing training opportunities to students and post-docs to help assure a vibrant workforce essential to the technologies associated with isotope production. Priorities in research isotope production are informed by guidance from NSAC as described in the 2015 Long Range Plan for the DOE Isotope Program published in July 2015 under the title "Meeting Isotope Needs and Capturing Opportunities for the Future[a]." The Isotope Program also supports research to implement modern stable isotope enrichment devices to provide the Nation with enrichment capabilities that have been absent since the DOE calutrons ceased operation in 1998. The U.S. is currently dependent on foreign sources for supplies of stable isotopes; the U.S. inventory has been depleted in the cases of some specific isotopes. Since FY 2017, the program has been able to produce small-scale research quantities of enriched stable isotopes. The R&D program also develops domestic production capabilities for important radioisotopes for which the U.S. has demand and/or which the U.S. is dependent on foreign sources.

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

A high priority is a dedicated research effort to develop large scale production capabilities of actinium-225, a high priority isotope that has shown stunning success in the treatment of diffuse cancers and infections; in the past, available quantities have limited clinical trials and applications. The Isotope Program commenced routine production of accelerator-produced Ac-225 in FY 2018 and is now ramping up production capabilities to enable sufficient supply of the isotope as a cancer therapeutic. Research efforts have demonstrated that the accelerator produced actinium-225 functions equivalently to the material derived from the decay of thorium-229 which used to be the only viable source of small quantities of actinium-225. In coordination with NIH, samples of the isotope produced by the accelerator production approach were evaluated by several different researchers involved in medical applications research to confirm these results.

Research supported for the past couple of years has culminated in the demonstration of reactor-produced actinium-227, representing the world's first source of new material. Actinium-227 decays to radium-223, which is used in new radiopharmaceutical drugs to treat prostate cancer. The provision of actinium-227 by the Isotope Program ensures that prostate cancer patients can have a reliable supply of palliative care drugs.

Operations

The Isotope Program is the steward of the Isotope Production Facility (IPF) at LANL, the BLIP facility at BNL, and hot cell facilities for processing and handling irradiated materials and purified products at ORNL, BNL, and LANL. Funding provides mission readiness for isotope production at all of these facilities, as well as facilities at other sites, such as the Idaho National Laboratory reactor for the production of cobalt-60, the PNNL for processing and packaging strontium-90, the Y-12 National Security Complex for processing and packaging lithium-6 and lithium-7, the LANL Plutonium Facility for extracting americium-241 from NNSA plutonium processes, the Low Energy Accelerator Facility (LEAF) at Argonne National Laboratory for the production of the medical isotope copper-67, and the Savannah River Site for the extraction and distribution of helium-3. Funding supports the essential personnel and infrastructure to ensure mission readiness for the production of isotopes; the isotope production costs are paid by the customer. Modest capital investments enable substantial and compelling enhancements to productivity, including new approaches to extract additional He-3 from new sources; the fabrication of a prototype production capability for Li-7, pertinent to next generation nuclear reactors; and upgrades to hot cell facilities at ORNL and LANL to increase radioisotope processing capabilities to keep up with new isotopes being produced for the community, including Ac-225.

In addition to isotope production at DOE facilities, the Isotope Program is funding production at universities with capabilities beyond those available at the stewarded facilities, such as an alpha-particle cyclotron at the University of Washington where full-scale production of astatine-211 was developed to support research into the use of the isotope in cancer therapy, and the University of Missouri Research Reactor where the Isotope Program supported the development of reactor production of selenium-75 for industrial gamma radiography. The establishment of a coordinated network of university-based isotope production was a recommendation in the 2015 NSAC-Isotope Long Range Plan. The network is designed to leverage the unique and often underutilized facilities available at academic institutions which are generally more suited to low-energy production reactions and can support nationwide availability of short-lived radioisotopes. Also, in anticipation of the opportunity FRIB will provide as a unique source of many important isotopes for research and applications, scientists are implementing the capability to harvest some of the isotopes that will be produced during physics research experiments. The Request includes funding to initiate this accelerator improvement project, the FRIB Isotope Harvesting project.

The DOE Isotope Program supports operations of ESIPP to produce research quantities of enriched stable isotopes through the use of electromagnetic separation and centrifuge technology. The first campaign run at ESIPP produced ruthenium-96 in FY 2018 to provide the otherwise unavailable target material world-wide to RHIC for its planned physics program. Modest investments develop new and different enriched stable isotope and enriched radioisotope production capabilities. The Isotope Program participates in the Office of Science QIS initiative to develop production approaches for enriched stable isotopes of interest for future QIS-driven technologies.

The SIPF MIE was initiated in FY 2017 to establish kilogram production capability of select isotopes to help meet the nation's demand for enriched stable isotopes for basic research, medical, national security and industrial applications as recommended by the NSAC Subcommittee on Isotopes in 2015. The SIPF MIE will reduce the nation's dependence for some critical isotopes on a foreign source and has a technically-driven profile for completion in FY 2024. SIPF adds additional gas centrifuge capability to the existing ESIPP. Examples of discovery research efforts that could benefit from the facility are neutrinoless double beta decay experiments and high energy physics dark matter experiments interested in kilogram quantities of enriched stable isotopes, which are not presently available in the U.S. Similarly, the accelerator-production route for Mo-99, a critical medical isotope for cardiac imaging, relies on a feedstock of enriched Mo isotopes, which are also unavailable domestically. Stable isotopic nuclides of heavier elements used for agricultural, nutritional, industrial, ecological, and computing applications can also be produced. SIPF will be able to partially meet the demands for these isotopes serially.

The capabilities of SIPF and ESIPF are not adequate to meet the quickly rising demands of the Nation for enriched stable isotopes. Additional capabilities in both electromagnetic ion separation and gas centrifuge capability are needed for the U.S. to play a strong role in this arena and operate multiple production lines simultaneously. Funding is requested in the FY 2020 Request to initiate construction of the U.S. Stable Isotope Production and Research Center (U.S. SIPRC) to consolidate stable isotope efforts throughout ORNL into a new building, and enhance electromagnetic ion separation and gas centrifuge production capabilities for enriched stable isotopes.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Isotope Development and Production for Research and Applications	**$44,259,000**	**$51,000,000**	**+$6,741,000**
Research	$9,808,000	$12,000,000	+$2,192,000
High priority competitive R&D activities continue at universities and national laboratories leading to new isotope production technologies. Core support will continue to be provided to national laboratories and universities for R&D that enhances isotope production capabilities.		Increased funding will support high priority competitive R&D activities at universities and national laboratories leading to new isotope production technologies. Core support will continue to be provided to national laboratories and universities for R&D that enhances isotope production capabilities specifically relevant to the physical resources and expertise available at the institution. Funding supports the development of two new core R&D groups, one at MSU to support the new isotope harvesting capability being established at FRIB, and the other at ANL to support the new isotope production effort at the LEAF electron facility at ANL.	Increased funding supports additional compelling efforts at universities and national laboratories in isotope production and processing research. The Request strengthens support for core research groups at the national laboratories and universities and nurtures two new core R&D groups, one at MSU for isotope harvesting and the other at ANL related to isotope production at LEAF.
Operations	$34,451,000	$39,000,000	+$4,549,000
The FY 2019 Enacted budget supports mission readiness of the isotope production facilities and the essential core competencies in isotope production and development, ensuring that isotope orders for cancer therapy and other commitments are reliably met. NIDC activities will support the effective interfaces with the growing stakeholder community. Funding supports mission readiness and operations of the ESIPP for the production of important enriched stable isotopes for the nation. The budget provides support to develop production approaches for stable		Increased funding fully supports mission readiness of the isotope production facilities and nurtures critical core competencies in isotope production and development, ensuring that isotope orders for cancer therapy and other commitments are reliably met. The Request provides a modest increase for NIDC activities to effectively interface with the growing stakeholder community and isotope portfolio. Increased funding permits a stronger and expanded University Isotope Production Network and increased ESIPP operations. Increased funding will provide	The funding for SIPF ramps down according to the planned profile. This decrease is offset with increases for robust mission readiness of isotope production and processing facilities, university isotope production, NIDC workforce to address the growing isotope portfolio, and development of isotope production approaches of importance for QIS, and modest and compelling investments in developing new production and processing capabilities including: new extraction techniques for He-3 from new

FY 2019 Enacted	FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
isotopes of interest for next generation QIS-driven technologies. The SIPF MIE is supported at its planned level. Funding supports the addition of new universities into the National University Isotope Production Network, which will emphasize production of astatine-211 for cancer therapy.	support to develop production approaches for isotopes of interest for next generation QIS-driven technologies. The FY 2020 Request includes final funding for the SIPF MIE, according to the planned profile. Investments will also provide support to develop new production and processing capabilities including: new extraction techniques for He-3 from new supplies, highly enriched Li-7 prototype production capabilities for next-generation nuclear reactors, electromagnetic separation production approaches optimized to heavy elements, enriched radioisotope separation, infrastructure investments to enhance processing capabilities, and the initiation of isotope harvesting capabilities at FRIB.	supplies, and the initiation of isotope harvesting capabilities at FRIB.

Nuclear Physics
Construction

Description

Consistent with the 2015 NSAC Long-Range Plan's highest priority, the FY 2020 Request includes funding to capitalize on NP's prior scientific facilities investments. Funding in this subprogram provides for design and construction of scientific research facilities needed to meet overall objectives of the Nuclear Physics program. NP currently has one ongoing project, which receives construction line item funding in FY 2020; one new project, which receives initial Other Project Costs in this Request in the Nuclear Theory subprogram; and another new project which receives initial construction funding in the Isotope Program subprogram.

The FRIB at MSU will continue construction activities in FY 2020, with a funding request aligned to the current baseline. The project is proceeding on track within the established project baseline and working towards an "early finish," FRIB will provide intense beams of rare isotopes for world-leading research opportunities in nuclear structure, nuclear astrophysics, and fundamental symmetry studies that will advance knowledge of the origin of the elements and the evolution of the cosmos. It offers a facility for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a broadly applicable theory of the structure of nuclei will emerge. FRIB will provide an essential scientific tool for over 1,400 scientists each year from across academic, industrial and government institutions. The project is funded through a cooperative agreement with MSU and was established as a control point in the FY 2014 appropriation. Prior to that time, funding was provided within the Low Energy subprogram.

The FY 2020 Request initiates a Total Project Cost start for the U.S. Stable Isotope Production and Research Center (U.S. SIPRC). The demand for enriched stable isotopes over the last decade has increased significantly. Demand drivers include enriched stables isotopes for medical, national security and fundamental research projects. DOE produced a legacy inventory of enriched stable isotopes using the former Y-12 plant Calutrons from the 1940s to 1990s, until they were decommissioned. DOE's supply of certain key enriched stable isotopes has been depleted or exhausted. Therefore the U.S. is becoming increasingly dependent on foreign imports for enriched stable isotopes. With support from the DOE Isotope Program, ORNL is advancing production capabilities for these stable isotopes, primarily electromagnetic isotope separation (EMIS) and gas centrifuge (GC) technologies. Electromagnetic isotope separators can separate isotopes for many elements to very high purity and at lower production rates while gas centrifuge production cascades can produce much larger quantities of isotopes but is limited to those isotopes that have compatible feedstock chemicals. The prototype capabilities of ESIPP, developed through DOE Isotope Program-supported research, demonstrated the feasibility of new EMIS and GC technology. The follow-on SIPF MIE, currently under construction, modestly increases GC production capability. SIPRC further expands GC production capability and significantly increases EMIS production capability to meet the Nation's growing demand for stable isotopes. To date, the current and modest production capabilities have been housed in several refurbished facilities; however, given the mission need for continued expansion of production capacity, the use of refurbished facilities is not optimal. Therefore, SIPRC will include a new facility at ORNL to integrate aspects of the stable isotope program such as EMIS and GC technologies; R&D units; and storage and dispensing operations. The new single facility will promote operational, cost and security effectiveness, with space for future growth, if needed. SIPRC will mitigate the Nation's dependence on foreign countries for stable isotope supply. Critical Decision-0 (CD-0), Approve Mission Need, was awarded in January of 2019 with a preliminary Total Project Cost Range of $150 – 200M at the time of CD-0.

Activities and Explanation of Changes

FY 2019 Enacted		FY 2020 Request	Explanation of Changes FY 2020 Request vs FY 2019 Enacted
Construction	**$75,000,000**	**$45,000,000**	**-$30,000,000**
14-SC-50, Facility for Rare Isotope Beams (FRIB)	$75,000,000	$40,000,000	-$35,000,000
The FY 2019 Enacted funding supports the ongoing fabrication, assembly and testing of cryomodules that will also be installed and tested in the newly constructed tunnel. Other technical systems, such as the experimental related systems will also be fabricated, assembled, installed and tested. As the various systems near completion, the linear accelerator commissioning effort will occur to validate their performance according to project requirements.		The FY 2020 Request will continue to support the fabrication, assembly, and testing of cryomodules, as well as their installation within the FRIB linear accelerator located in the tunnel area. As portions of the linear accelerator nears completion, commissioning efforts will also continue in order to validate accelerator's performance according to project requirements. In addition, fabrication, assembly, installation and testing of the experimental technical systems will continue; project completion is planned in FY 2022.	FRIB construction funding continues according to its baseline profile.
20-SC-51, U.S. Stable Isotope Production and Research Center (ORNL)	$—	$5,000,000	+$5,000,000
Funding in FY 2019 provides for the development of a conceptual design of the U.S. Stable Isotope Production and Research Center (U.S. SIPRC).		FY 2020 funding is requested for engineering design of the U.S. SIPRC and long lead procurements for known designs of technologies developed for prior efforts, ESIPP and SIPF.	Funding is requested to initiate the Total Estimated Cost ($150,000,000-$200,000,000) of the U.S. SIPRC.

Nuclear Physics
Capital Summary

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Capital Operating Expenses Summary						
Capital equipment	N/A	N/A	22,402	38,025	17,418	-20,607
Minor Construction Activities						
General Plant Projects (GPP)	N/A	N/A	2,000	2,060	9,500	+7,440
Accelerator Improvement Projects (AIP)	N/A	N/A	4,929	5,077	6,929	+1,852
Total, Capital Operating Expenses	**N/A**	**N/A**	**29,331**	**45,162**	**33,847**	**-11,315**

Nuclear Physics
Capital Equipment

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Capital Equipment						
Major Items of Equipment (MIE)						
Medium Energy Nuclear Physics						
MOLLER MIE	25,000-35,000	N/A	N/A	—	300	+300
Heavy Ion Nuclear Physics						
Super-PHENIX (sPHENIX) MIE[a]	24,200-34,500	N/A	N/A	5,310	3,000	-2,310
Low Energy Nuclear Physics						
Gamma-Ray Energy Tracking Array (GRETA) MIE	52,000–65,000[b]	N/A	5,200	6,600	2,500	-4,100
High Rigidity Spectrometer (HRS)[c]	80,000-90,000	N/A	N/A	—	1,000	+1,000
Neutrinoless Double Beta Decay MIE	215,000-250,000	N/A	N/A	—	1,440	+1,440
Isotope Development and Production for Research and Development						
Stable Isotope Production Facility (SIPF) MIE	25,500–28,000	N/A	10,000	11,500	1,500	-10,000
Total Non-MIE Capital Equipment	N/A	N/A	7,202	14,615	7,678	-6,937
Total, Capital Equipment	**N/A**	**N/A**	**22,402**	**38,025**	**17,418**	**-20,607**

[a] sPHENIX MIE will be funded through existing operations funding which would typically be used to operate the previous version of the detector, PHENIX; no new funds are required.

[b] Total Project Cost range

[c] HRS will be funded through a cooperative agreement with MSU and is not a capital asset.

Nuclear Physics
Minor Construction Activities

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
General Plant Projects						
Greater than or equal to $5M and less than $20M						
End Station Refrigerator at TJNAF	9,500	—	—	—	9,500	+9,500
Total GPPs, greater than or equal to $5M and less than $20M	9,500	—	—	—	9,500	+9,500
Total GPPs less than $5M[a]	N/A	N/A	2,000	2,060	—	-2,060
Total, General Plant Projects (GPP)	**N/A**	**N/A**	**2,000**	**2,060**	**9,500**	**+7,440**
Accelerator Improvement Projects (AIP)						
Greater than or Equal to $5M and less than $20M						
RHIC Low Energy Electron Cooling	8,300	7,000	1,300	—	—	—
FRIB Isotope Harvesting[b]	9,000-11,000	N/A	N/A	—	2,000	+2,000
Total AIPs (greater than or equal to $5M and less than $20M)	N/A	N/A	1,300	—	2,000	+2,000
Total AIPs less than $5M	N/A	3,652	3,629	5,077	4,929	-148
Total, Accelerator Improvement Projects	**N/A**	**10,652**	**4,929**	**5,077**	**6,929**	**+1,852**
Total, Minor Construction Activities	**N/A**	**N/A**	**6,929**	**7,137**	**16,429**	**+9,292**

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

Nuclear Physics
Major Items of Equipment Description(s)

Medium Energy Nuclear Physics MIE:
The *Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER)* experiment directly supports the Nuclear Physics mission by measuring the parity-violating asymmetry in electron-electron (Møller) scattering. CD-0 was approved December 2016 with an estimated Total Project Cost of $25,000,000 to $35,000,000. The proposed MOLLER experiment is an ultra-precise measurement of the weak mixing angle using Møller scattering which will improve on existing measurements by a factor of five, yielding the most precise measurement of the weak mixing angle at low or high energy anticipated over the next decade. This new result would be sensitive to the interference of the electromagnetic amplitude with new neutral current amplitudes as weak as $\sim 10^{-3}$ GF 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 2020 Request for MOLLER of $300,000 is the first year of TEC funding.

Heavy Ion Nuclear Physics MIE:
The *Super Pioneering High Energy Nuclear Interaction Experiment (sPHENIX)* directly supports the Nuclear Physics 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 2016 with an estimated Total Project Cost of $29,000,000 to $35,000,000. CD-1/3a was approved in August 2018 with a TPC range of $24,200,000 to $34,500,000. This MIE is funded within the existing funds for RHIC operations. Operating funds that are typically used to maintain and operate the PHENIX detector will be used to upgrade the detector. No new funding is required. sPHENIX adds electron and hadron calorimeters to the existing silicon tracking capabilities and makes use of a recycled solenoid magnet for a cost effective upgrade. The FY 2020 Request for sPHENIX of $3,000,000 is the second year of TEC funding and below the planned amount; project plans will be re-evaluated upon an FY 2020 appropriation to consider changes to the project cost and schedule.

Low Energy Nuclear Physics MIEs:
The *Gamma-Ray Energy Tracking Array (GRETA) detector* 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 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 is needed to 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 in September 2015 with an estimated Total Project Cost (TPC) of $52,000,000–$67,000,000. CD-1 was obtained in September FY 2017. CD-3a was obtained in September 2018 with an estimated TPC of $52,000,000 - $65,000,000. The FY 2020 Request for GRETA of $2,500,000 is the fourth year of Total Estimated Cost (TEC) funding and is below the planned amount; project plans will be re-evaluated upon an FY 2020 appropriation to consider changes to the project cost and schedule.

The *High Rigidity Spectrometer (HRS) MIE*: FRIB will be the world's premier rare-isotope beam facility producing a majority (~80%) 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 HRS will increase the scientific reach by an order of magnitude for other state-of-the-art and community-priority devices, such as the GRETA, in addition to other ancillary detectors. The 2015 NSAC LRP recognized that the "*HRS…will be essential to realize the scientific reach of FRIB"*. The FY 2020 Request for the HRS of $1,000,000 is the first year of funding. The HRS will be funded through a cooperative agreement with MSU and is not a capital asset. CD-0 was approved November 2018 with a TPC range of $80,000,000 - $90,000,000.

The *Ton-Scale Neutrino-less Double Beta Decay (NLDBD) Experiment* MIE, implemented by instrumenting a large volume of a specially selected isotope to detect neutrino-less nuclear beta decays (within a single nucleus, two neutrons decay into two protons and two electrons with no neutrinos emitted) directly supports DOE NP's mission to explore all forms of nuclear matter. Neutrino-less double beta decay 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, game changing consequences for present understanding of the physical universe. For example, one exciting prospect is that the observation of neutrino-less double beta decay would elucidate the mechanism, completely unknown at present, by which the mass of the neutrino is generated. The observation of lepton number violation would also have major implication for the present day matter/anti-matter asymmetry which has perplexed modern physics for decades. In the current experimental outlook, through FY 2018 a number of demonstrator efforts using smaller volumes of isotopes and various technologies (bolometry in TeO2 crystals, light collection in LXe, charge collection in enriched Ge-76) have been in progress for several years, and all are in the process of delivering new state-of-the-art lifetime limits for 0[illegible] 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^{27} to 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 (5-10 years) similar to other large modern physics experiments. The FY 2020 Request for a Ton Scale Neutrino-less Double Beta Decay Experiment is $1,440,000 in the first year of TEC funding. CD-0 was approved November 2018 with a TPC range of $215,000,000 - $250,000,000.

<u>Isotope Development and Production for Research and Applications MIE:</u>
The *Stable Isotope Production Facility (SIPF).* The DOE Isotope Program has invested funds since 2009 to develop stable isotope separation technology at ORNL, first identified as a high priority by the NSAC Subcommittee on Isotopes in 2009. NP completed an R&D effort in 2017, which has resulted in a prototype capability to produce small research quantities of enriched stable isotopes. The prototype demonstration has been established in a facility that can be expanded and the resulting capability is completely scalable to produce kilogram quantities of enriched stable isotopes in a cost-effective manner. There is a high demand for a domestic capability to produce enriched stable isotopes for basic research, medical and industrial applications. For example, foreign neutrinoless double beta decay experiments in nuclear physics and dark matter experiments in high-energy physics are interested in kg quantities of enriched stable isotopes, which are not available in the U.S. The accelerator production route for Mo-99, a critical medical isotope for cardiac imaging, which is being supported by NNSA, relies on a feedstock of enriched Mo isotopes, which are also not available domestically. Stable isotopic nuclides of heavier elements are used for agricultural, nutritional, industrial, ecological and computing applications could also be produced. The FY 2017 appropriation initiated this Major Item of Equipment to initiate fabrication of a domestic production facility for full-scale production of stable enriched isotopes to help mitigate the dependence of the U.S. on foreign suppliers and meet the high demands for enriched stable isotopes for the Nation. MIE funding provides infrastructure, and optimizes the design of centrifuges to isotopes of interest. CD-0 was approved September 2015 with an estimated TPC of $9,500,000–$10,500,000. CD-1/3a was approved in May 2018 with an estimated TPC range of $25,500,000-$28,000,000. The FY 2020 Budget requests the final year of funding for SIPF.

Nuclear Physics
Construction Projects Summary

(dollars in thousands)

	Total	Prior Years	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
14-SC-50, Facility for Rare Isotope Beams						
DOE TPC	635,500[a]	418,000[b]	97,200	75,000	40,000	-35,000
20-SC-51, U.S. Stable Isotope Production and Research Center						
TPC	150,000-200,000	—	—	—	5,000	+5,000
Total, Construction (TPC)	**N/A**	**N/A**	**97,200**	**75,000**	**45,000**	**-30,000**

Funding Summary

(dollars in thousands)

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Research	180,502	204,095	172,476	-31,619
Scientific User Facilities Operations	324,250	336,145	333,038	-3,107
Other Facility Operations	24,200	27,586	41,800	+14,214
Projects (includes Other Project Costs)				
Major Items of Equipment	15,200	23,410	9,740	-13,670
Facility for Rare Isotope Beams	97,200	75,000	40,000	-35,000
U.S. Stable Isotope Production and Research Center	—	—	5,000	+5,000
Electron Ion Collider (OPC)	—	—	1,500	+1,500
Total, Projects	112,400	98,410	56,240	-42,170
Other[c]	23,400	23,764	21,300	-2,464
Total, Nuclear Physics	**684,000**	**690,000**	**624,854**	**-65,146**

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

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

[c] Includes SBIR/STTR funding.

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:

Achieved Operating Hours – The amount of time (in hours) the facility was available for users.

Planned Operating Hours –

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

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

Percent of Optimal Hours – An indication of utilization effectiveness in the context of available funding; it is not a direct indication of scientific or facility productivity.

- For BY and CY, Planned Operating Hours divided by Optimal Hours (OH) expressed as a percentage
- For PY, Achieved Operating Hours divided by Optimal Hours.

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

(dollars in thousands)

	FY 2018 Enacted	FY 2018 Current	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
TYPE A FACILITIES					
CEBAF (TJNAF)[a]	**$122,930**	**$123,810**	**$128,067**	**$124,964**	**-3,103**
Number of Users	1,600	1,615	1,615	800	-815
Achieved operating hours	N/A	2,415	N/A	N/A	N/A
Planned operating hours	2,660	2,660	4,080	1,020	-3,060
Optimal hours	2,660	2,660	4,250	4,320	+70
Percent optimal hours	100.0%	90.8%	96.0%	23.6%	-72.4%
Unscheduled downtime hours	—	—	N/A	N/A	N/A

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

(dollars in thousands)

	FY 2018 Enacted	FY 2018 Current	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
RHIC (BNL)	**$194,022**	**$194,048**	**$199,705**	**$192,116**	**-7,589**
Number of Users	988	988	985	985	—
Achieved operating hours	N/A	4,055	N/A	N/A	N/A
Planned operating hours	3,170	4,054	3,290	1,500	-1,840
Optimal hours	3,170	3,170	3,700	3,700	—
Percent optimal hours[a]	100.0%	127.9%	88.9%	40.5%	-48.4%
Unscheduled downtime hours	—	—	N/A	N/A	N/A
ATLAS (ANL)	**$25,481**	**$25,241**	**$25,947**	**$22,756**	**-3,191**
Number of Users	360	208	410	145	-265
Achieved operating hours	N/A	5,747	N/A	N/A	N/A
Planned operating hours	5,800	5,800	6,400	2,090	-4,310
Optimal hours	6,600	6,600	6,800	6,800	—
Percent optimal hours	87.9%	87.1%	94.1%	30.7%	-63.4%
Unscheduled downtime hours	—	—	N/A	N/A	N/A
FRIB (MSU)	**$3,750**	**$3,750**	**$3,950**	**$13,538**	**+9,588**
Number of Users	N/A	N/A	N/A	N/A	N/A
Achieved operating hours	N/A	N/A	N/A	N/A	N/A
Planned operating hours	N/A	N/A	N/A	N/A	N/A
Optimal hours	N/A	N/A	N/A	N/A	N/A
Percent optimal hours	N/A	N/A	N/A	N/A	N/A
Unscheduled downtime hours	N/A	N/A	N/A	N/A	N/A

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

(dollars in thousands)

	FY 2018 Enacted	FY 2018 Current	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Total Facilities	**$346,183**	**$346,849**	**$357,669**	**$353,374**	**-4,295**
Number of Users	2,948	2,811	3,010	1,930	-1,080
Achieved operating hours	N/A	12,217	N/A	N/A	N/A
Planned operating hours	8,970	12,514	13,770	4,610	-9,160
Optimal hours	12,430	12,430	14,750	14,820	+70
Percent of optimal hours[a]	100.0%	127.9%	91.9%	31.1%	-60.8%
Unscheduled downtime hours	—	—	N/A	N/A	N/A

Scientific Employment

	FY 2018 Enacted	FY 2019 Enacted	FY 2020 Request	FY 2020 Request vs FY 2019 Enacted
Number of permanent Ph.D.'s (FTEs)	825	830	814	-16
Number of postdoctoral associates (FTEs)	330	350	317	-33
Number of graduate students (FTEs)	530	550	461	-89
Other[b]	1,035	1,060	958	-102

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

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

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

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

Summary

The FY 2020 Request for the Facility for Rare Isotope Beams (FRIB) project is $40,000,000. The most recent Critical Decision (CD) for the FRIB project is CD-3B, Approve Start of Technical Construction of the Accelerator and Experimental Systems, which was approved on August 26, 2014, with a DOE Total Project Cost (TPC) of $635,500,000, and a scheduled CD-4 by 3Q FY 2022. Michigan State University (MSU) is providing an additional cost share of $94,500,000, bringing the total project cost to $730,000,000.

Significant Changes

This PDS is an update of the FY 2019 PDS and does not include a new start for FY 2020.

Start of civil construction officially began in March 2014, and technical construction began in August 2014. Since the start of the civil and technical construction, multiple independent project assessments, the most recent being in November 2018, have determined the project is proceeding on track and within the established project baseline. There are no changes in the project's scope since the establishment of the project's baseline.

FRIB is funded through a cooperative agreement financial assistance award with MSU per 10 CFR 600, and the project is required by this agreement to follow the principles of the DOE Order 413.3B. Funding tables contained in sections 3 and 4 of this Project Data Sheet (PDS) differ slightly from a traditional PDS for a federal capital asset construction project for how the baseline is presented in that they include the MSU cost share. The table in section 5, Schedule of Appropriations Requests, displays only DOE funding.

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

Critical Milestone History

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3A	CD-3B	D&D Complete	CD-4
FY 2011	2/9/2004		4Q FY 2010	TBD	TBD	TBD	TBD	N/A	FY 2017–2019
FY 2012	2/9/2004		9/1/2010	4Q FY 2012	TBD	TBD	TBD	N/A	FY 2018–2020
FY 2013	2/9/2004		9/1/2010	TBD	TBD	TBD	TBD	N/A	TBD
FY 2014	2/9/2004		9/1/2010	3Q FY 2013	TBD	3Q FY 2013	TBD	N/A	TBD
FY 2015	2/9/2004		9/1/2010	8/1/2013	4Q FY 2014	8/1/2013	4Q FY 2014	N/A	3Q FY 2022
FY 2016	2/9/2004	9/1/2010	9/1/2010	8/1/2013	8/26/2014 [a]	8/1/2013	8/26/2014	N/A	3Q FY 2022
FY 2017	2/9/2004	9/1/2010	9/1/2010	8/1/2013	8/26/2014[a]	8/1/2013	8/26/2014	N/A	3Q FY 2022

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

Fiscal Year	CD-0	Conceptual Design Complete	CD-1	CD-2	Final Design Complete	CD-3A	CD-3B	D&D Complete	CD-4
FY 2018	2/9/2004	9/1/2010	9/1/2010	8/1/2013	8/26/2014	8/1/2013	8/26/2014	N/A	3Q FY 2022
FY 2019	2/9/2004	9/1/2010	9/1/2010	8/1/2013	8/26/2014	8/1/2013	8/26/2014	N/A	3Q FY 2022
FY 2020	2/9/2004	9/1/2010	9/1/2010	8/1/2013	8/26/2014	8/1/2013	8/26/2014	N/A	3Q FY 2022

CD-0 – Approve Mission Need
CD-1 – Approve Alternative Selection and Cost Range
CD-2 – Approve Performance Baseline
CD-3A – Approve Start of Civil Construction
CD-3B – Approve Start of Technical Construction
D&D Complete – Completion Demolition & Decontamination
CD-4 – Approve Start of Operations or Project Closeout

Project Cost History[a]

(dollars in thousands)

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

2. Project Scope and Justification

Scope

FRIB scope includes the design, construction, fabrication, assembly, testing, and commissioning of the civil and technical scope that will enable high intensity primary beams of stable isotopes to be accelerated up to a minimum energy of 200 MeV per nucleon by a superconducting linear accelerator (linac) capable of delivering 400 kW of beam power at full energy. The scope also includes the capability for secondary beams of rare isotopes to be produced “in-flight” and separated from unwanted fragments by magnetic analysis. In support of these capabilities, the civil construction portion includes a structure of approximately 220,000 square feet that will house the linac tunnel, target high bay area, linac support area, and cryoplant area. The technical scope includes a 2K/4.5K cryogenics plant, linac front end, cryomodules, and experimental systems.

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

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

Justification

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

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

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

Key Performance Parameters (KPPs)

System	Parameter	Performance Criteria
Accelerator System	Accelerate heavy-ion beam	Measure FRIB driver linac Argon-36 beam with energy larger than 200 MeV per nucleon and a beam current larger than 20 pico nano amps (pnA)
Experimental Systems	Produce a fast rare isotope beam of Selenium-84	Detect and identify Selenium-84 isotopes in FRIB fragment separator focal plane
	Stop a fast rare isotope beam in gas and reaccelerate a rare isotope beam	Measure reaccelerated rare isotope beam energy larger than 3 MeV per nucleon
Conventional Facilities	Linac tunnel	Beneficial occupancy of subterranean tunnel structure of approximately 500 feet path length (minimum) to house FRIB driver linear accelerator
	Cryogenic helium liquefier plant—building and equipment	Beneficial occupancy of the cryogenic helium liquefier plant building and installation of the helium liquefier plant complete
	Target area	Beneficial occupancy of target area and one beam line installed and ready for commissioning

3. Financial Schedule[a]

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs[b]
DOE Total Project Cost (TPC)			
FY 2009	7,000	7,000	4,164
FY 2010	12,000	12,000	13,283
FY 2011	10,000	10,000	11,553
FY 2012	22,000	22,000	18,919
FY 2013	22,000	22,000	20,677
FY 2014[c]	55,000	55,000	48,369
FY 2015	90,000	90,000	79,266
FY 2016	100,000	100,000	121,769
FY 2017	100,000	100,000	100,000
FY 2018	97,200	97,200	84,124
FY 2019	75,000	75,000	70,000
FY 2020	40,000	40,000	30,000
FY 2021	5,300	5,300	15,300
FY 2022	—	—	18,076
Total, DOE TPC	**635,500**	**635,500**	**635,500**

4. Details of Project Cost Estimate[d]

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
DOE Total Project Costs (TPC)			
Design & Construction			
Management and Support	37,288	37,153	35,400
Conventional Facilities	208,100	208,100	165,300
Accelerator Systems	295,216	289,726	241,400
Experimental Systems	75,520	74,207	55,000
Contingency (DOE Held)	39,626	46,564	158,650
Total, Design & Construction	655,750	655,750	655,750

[a] The funding profile represents DOE's requested portion, which is less than the current baselined TPC which includes MSU's cost share.

[b] Costs through FY 2018 reflect actual costs; costs for FY 2019 and the outyears are estimates.

[c] The first project data sheet submitted for FRIB was in the FY 2015 Congressional Budget Request. It was established as a control point in the FY 2014 appropriation. Funding for the project in FY 2013 and prior years was provided within the Low Energy subprogram.

[d] This section shows a breakdown of the total project cost of $730,000,000 as of 6/30/2018, which includes MSU's cost share. The scope of work is not pre-assigned to DOE or MSU funds.

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Baseline
Other Costs			
Conceptual Design/Tech R&D/NEPA	24,641	24,641	24,600
Pre-ops/Commissioning/Spares	34,659	34,659	35,500
Contingency (DOE Held)	14,950	14,950	14,150
Total, Other Costs	74,250	74,250	74,250
Total, TPC	**730,000**	**730,000**	**730,000**
MSU Cost Share	*94,500*	*94,500*	*94,500*
Total Project Costs (DOE Share)	**635,500**	**635,500**	**635,500**
Total, Contingency (DOE Held)	***54,576***	***61,514***	***172,800***

5. Schedule of Appropriations Requests[a]

(dollars in thousands)

Request Year	Type	Prior Years	FY 2018	FY 2019	FY 2020	FY 2021	Total
FY 2011	TPC	29,000	—	—	—	—	29,000
FY 2012	TPC	59,000	—	—	—	—	59,000
FY 2013	TPC	73,000	—	—	—	—	73,000
FY 2014	TPC	128,000	—	—	—	—	128,000
FY 2015	TPC	418,000	97,200	75,000	40,000	5,300	635,500
FY 2016	TPC	418,000	97,200	75,000	40,000	5,300	635,500
FY 2017	TPC	418,000	97,200	75,000	40,000	5,300	635,500
FY 2018	TPC	418,000	80,000	75,000	57,200	5,300	635,500
FY 2019	TPC	418,000	80,000	75,000	57,200	5,300	635,500
FY 2020	TPC	418,000	97,200	75,000	40,000	5,300	635,500

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy (fiscal quarter or date)	3Q FY 2022
Expected Useful Life (number of years)	20
Expected Future Start of D&D of this capital asset (fiscal quarter)	N/A[b]

Related Funding Requirements
(dollars in thousands)

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

[a] The funding profile represents DOE's portion of the baselined TPC to be provided through federal appropriations.

[b] Per the financial assistance award agreement, MSU is responsible for D&D.

[c] Utilities, maintenance, and repair costs are included within the Operations amounts.

[d] The total operations and maintenance (O&M) is estimated at an average annual cost of approximately $90,000,000 (including escalation) over 20 years.

7. D&D Information

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

8. Acquisition Approach

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

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

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

Summary

The FY 2020 request for the United States Stable Isotope Production and Research Center (U.S. SIPRC) is $5,000,000. The most recent DOE O 413.3B approved Critical Decision (CD) is CD-0, Approve Mission Need, which was approved on January 4, 2020, with a preliminary Total Project Cost (TPC) range of $150,000,000 to $200,000,000.

Significant Changes

This project data sheet (PDS) is a new start for budget year FY 2020.

FY 2020 funding will support Project Engineering and Design activities. Other Project Cost (OPC) funded conceptual design work commenced in 2Q FY2019. Pre-conceptual design and research and development for this initiative are highly leveraged and advanced by prior efforts related to the technology that will be used by U.S. SIPRC. These prior efforts include the completed Electromagnetic Isotope Production Prototype and the ongoing Stable Isotope Production Facility (SIPF) Major Item of Equipment.

A Federal Project Director (FPD) has not been assigned to the U.S. SIPRC, but one will be assigned by CD-1.

Critical Milestone History

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

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

Fiscal Year	TEC, Design	TEC, Construction	TEC, Total	OPC Except D&D	OPC, D&D	OPC, Total	TPC
FY 2020	TBD	TBD	TBD	TBD	TBD	TBD	TBD

2. Project Scope and Justification

Scope

The scope of this project includes additional electromagnetic isotope separator systems and gas centrifuge cascades housed in a new single facility to promote operational, cost and security effectiveness, with space for future growth. The facility

[a] Dates presented are as approved at CD-0 and are notional, i.e., they will change as the conceptual design is developed.

includes adequate space for test stands and prototype development and is a purely technical facility (i.e., minimal office and staff amenities) and located on the ORNL main campus. Gas centrifuges and electromagnetic separators are based on existing designs developed from prior projects and R&D supported by DOE IP. As part of the alternatives analysis for Critical Decision-1 (CD-1), the optimal number of each type of technology is being considered.

Justification

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

The proposed U.S. SIPRC at ORNL will integrate all aspects of the stable isotope program, including electromagnetic separation and centrifuge technologies; research and development laboratories; stable isotope storage and dispensing operations; and technical services for preparing special isotope forms through physical and chemical conversions. U.S. SIPRC will expand current production capabilities for enriched stable isotopes and provide a new building that will facilitate efficient operations and provide space, not only for all of the current needs, but will also accommodate the projected large-scale expansion of production systems.

Key Performance Parameters (KPPs)

Performance Measure	Threshold	Objective
TBD	TBD	TBD

This project is at CD-0. Preliminary Key Performance Parameters will be created in support of CD-1, Approve Alternative Selection and Cost Range.

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

3. Financial Schedule

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Cost (TEC)			
PED			
FY 2020	5,000	5,000	4,000
FY 2021	TBD	TBD	TBD
Total, PED	TBD	TBD	TBD
Construction			
FY 2020	—	—	—
FY 2021	TBD	TBD	TBD
Total, Construction	TBD	TBD	TBD

(dollars in thousands)

	Budget Authority (Appropriations)	Obligations	Costs
Total Estimated Costs (TEC)			
FY 2020	5,000	5,000	4,000
FY 2021	TBD	TBD	TBD
Total, TEC	**TBD**	**TBD**	**TBD**
Other Project Costs (OPC)			
OPC except D&D			
FY 2019	500	500	400
FY 2020	—	—	100
Total, OPC	**TBD**	**TBD**	**TBD**
Total Project Costs (TPC)			
FY 2019	500	500	400
FY 2020	5,000	5,000	4,100
FY 2021	TBD	TBD	TBD
Total, TPC[a]	**TBD**	**TBD**	**TBD**

4. Details of Project Cost Estimate

(dollars in thousands)

	Current Total Estimate	Previous Total Estimate	Original Validated Estimate
Total Estimated Cost (TEC)			
Design			
Design	5,000	N/A	N/A
Contingency	—	N/A	N/A
Total, Design	TBD	N/A	N/A
Construction			
Construction	TBD	N/A	N/A
Contingency	TBD	N/A	N/A
Total, Construction	TBD	N/A	N/A
Total, TEC	**5,000**	**N/A**	**N/A**
Contingency, TEC	*TBD*	*N/A*	*N/A*
Other Project Cost (OPC)			
OPC except D&D			
Conceptual Design	500	N/A	N/A
R&D	TBD	N/A	N/A
Start-up	TBD	N/A	N/A
Contingency	TBD	N/A	N/A
Total, OPC	**500**	**N/A**	**N/A**
Contingency, OPC	*TBD*	*N/A*	*N/A*
Total Project Cost[a]	**TBD**	**N/A**	**N/A**
Total, Contingency (TEC+OPC)	***TBD***	***N/A***	***N/A***

[a] This request is for FY 2020 Design costs only. This project is at CD-0 and therefore is not baselined.

5. Schedule of Appropriation Requests

Request Year	Type	Prior Years	FY 2019	FY 2020	Outyears	Total
FY 2020	TEC	—	—	5,000	—	TBD
(Design only)	OPC	—	500	—	—	TBD
	TPC	—	500	5,000	—	TBD

6. Related Operations and Maintenance Funding Requirements

Start of Operation or Beneficial Occupancy (fiscal quarter or date)	TBD
Expected Useful Life (number of years)	TBD
Expected Future start of D&D for new construction (fiscal quarter)	TBD

Related Funding Requirements
(dollars in thousands)

	Annual Costs		Life cycle costs	
	Previous Total Estimate	**Current Total Estimate**	**Previous Total Estimate**	**Current Total Estimate**
Operations and Maintenance	TBD	TBD	TBD	TBD

7. D&D Information

	Square Feet
Area of new construction	TBD
Area of existing facility(ies) being replaced	TBD
Area of any additional D&D space to meet the “one-for-one” requirement	TBD

The “one-for-one” requirement will be met through an offset or waiver.

8. Acquisition Approach

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