A NEW ERA OF DISCOVERY

THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.5

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

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Abbreviations

A

aCORN	(experiment)
AI	artificial intelligence
ALICE	A Large Ion Collider Experiment
ALICE-USA	US component of ALICE collaboration
ANASEN	Array for Nuclear Astrophysics Studies with Exotic Nuclei
ANPhA	Asian Nuclear Physics Association
ARIEL	Advanced Rare Isotope Laboratory
ARUNA	Association for Research at University Nuclear Accelerators
ATLANTIS	Argonne Tandem Hall Laser Beamline for Atom and Ion Spectroscopy
ATLAS	Argonne Tandem Linac Accelerator
ATLAS	A Toroidal LHC Apparatus System

B

BCAL	barrel calorimeter
BeEST	Beryllium Electron Capture in Superconducting Tunnel Junctions Experiment
BEPC	Beijing Electron– Positron Collider
BES	Beam Energy Scan
BES-II	Beam Energy Scan–II
BES-III	Beam Energy Scan–III
BEST	Beam Energy Scan Theory (collaboration)
BigRIPS	Superconducting Radioactive Isotope Beam Separator
BLIP	Brookhaven Linac Isotope Producer
BNCT	boron neutron capture therapy
BNL	Brookhaven National Laboratory
BoNuS	(experiment)
BRIKEN	beta-delayed neutrons at RIKEN (experiment)
BSM	beyond the Standard Model

C

CA	community agreement
CARIBU	Californium Rare Isotope Breeder Upgrade
CASPAR	Compact Accelerator for Performing Astrophysical Research
CATS	Center for Accelerator Target Science
CBETA	Cornell Brookhaven Electron Test Accelerator
CBM	Compressed Baryonic Matter (experiment)
CD	Critical Decision
CEBAF	Continuous Electron Beam Accelerator Facility
CERN	European Organization for Nuclear Research
CEU	Conference Experience for Undergraduates
CHIPS	Creating Helpful Incentives to Produce Semiconductors
CJPL-II	China Jinping Underground Laboratory–II
CKM	Cabibbo–Kobayashi–Maskawa (matrix)
CLAS	CEBAF Large-Acceptance Spectrometer
CLFV	charged lepton flavor violation
CME	chiral magnetic effect
CMS	Compact Muon Solenoid
CNO	carbon–nitrogen–oxygen (cycle)
COHERENT	Coherent Elastic Neutrino–Nucleus Scattering (experiment)
COMPASS	Common Muon and Proton Apparatus for Structure and Spectroscopy (experiment)
CRES	cyclotron radiation emission spectroscopy
CREX	Calcium Radius Experiment
CSSI	Cyberinfrastructure for Sustained Scientific Innovation
CT	computerized tomography
CUORE	Cryogenic Underground Observatory for Rare Events
CUPID	CUORE Upgrade with Particle Identification

D

DESY	Deutches Elektronen-Synchrotron
DEVS	Discrete Event System Specification
DIS	deep inelastic scattering
DNP	Division of Nuclear Physics (within the American Physical Society)
DOE	US Department of Energy
DOE IP	DOE Isotope R&D and Production
DOE NP	DOE Office of Nuclear Physics
DOE SC	DOE Office of Science
DSSV	DEVS-based software simulation and validation methodology

E

EBIS	electron beam ion source
ECR	electron cyclotron resonance
EDM	electric dipole moment
EIC	Electron–Ion Collider

EIC-TA	EIC Theory Alliance
ELSA	Electron Stretcher Accelerator
EMC	See glossary
emiT	(experiment)
EOS	equation of state
ePIC	Electron–Proton/Ion Collider
EXO	Enriched Xenon Observatory
ExoHad	Exotic Hadron Collaboration

F

FAIR	Facility for Antiproton and Ion Research
FCAL	forward calorimeter 1
Fermilab	Fermi National Accelerator Laboratory
FDS	FRIB Decay Station
FDSi	FRIB Decay Station Initiator
FIONA	For the Identification of Nuclide A
FIRE	Fission in R-Process Elements (collaboration)
fIREBall	fInternal conveRsion Electron Ball
FLASH	ultrahigh dose rate
FLASH-RT	FLASH radiotherapy
FNPB	Fundamental Neutron Physics Beamline
FoCal	Forward Calorimeter
FRIB	Facility for Rare Isotope Beams
FRIB-TA	FRIB Theory Alliance
FSNN	fundamental symmetries, neutrons, and neutrinos
FSU	Florida State University

G

GANIL	Grand Accelerateur National d'Ions Lourds (National Large Heavy Ion Accelerator)
GERDA	Germanium Detector Array
GlueX	(experiment)
GlueX-II	(experiment)
GPD	generalized parton distribution
GRETA	Gamma-Ray Energy Tracking Array
GRETINA	Gamma-Ray Energy Tracking In-Beam Nuclear Array
GSI	GSI Helmholtz Centre for Heavy Ion Research

H

HEFTY	Heavy-Flavor Theory (collaboration)
HELIOS	Helical Orbit Spectrometer (instrument)
HERMES	(experiment)
HMS	High-Momentum Spectrometer
HPC	high-performance computing
HRS	High Rigidity Spectrometer
HRS-L	(instrument)
HRS-R	(instrument)
HUNTER	Heavy Unseen Neutrinos by Total Energy-Momentum Reconstruction (experiment)

I

ICPC	inverted coaxial point-contact
ICP-MS	Inductively coupled plasma mass spectrometry
INCITE	Innovative and Novel Computational Impact on Theory and Experiment (program)
INT	Institute for Nuclear Theory
INTT	intermediate silicon strip tracker (sPHENIX detector)
IQuS	InQubator for Quantum Simulation
IRA	Inflation Reduction Act
ISAC	Isotope and Accelerator (facility)
ISLA	Isochronous Spectrometer with Large Acceptances
ISOL	isotope separation online (method)
ISOLDE	Isotope Mass Separator On-Line

J

JETSCAPE	Jet Energy-Loss Tomography with a Statistically and Computationally Advanced Program Envelope (collaboration)
JFYL	Jyväskylä Department of Physics Accelerator Laboratory
JMU	James Madison University
J-PARC	Japan Proton Accelerator Research Complex

K

KamLAND-Zen	Kamioka Liquid Scintillator Antineutrino Detector–Zen (experiment)
KATRIN	Karlsruhe Tritium Neutrino Experiment
KEK	High-Energy Accelerator Research Organization (Japan)

L

LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBNL	Lawrence Berkeley National Laboratory
LEGEND	Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty (experiment)
LNGS	Gran Sasso National (Italy)
LSTAR	Light Ion Guide Separator for TAMU's Rare Isotope Beams (instrument)

LXe	liquid xenon

M

MAGIX	Mainz Gas Injection Target Experiment
MAJORANA	(experiment)
MARATHON	(experiment)
MESA	Mainz Energy Recovery Superconducting Accelerator
ML	machine learning
MOLLER	Measurement of a Lepton–Lepton Electroweak Reaction (experiment)
MPGD	Micropattern gaseous detector
MPS	Directorate for Mathematical and Physical Sciences (within NSF)
MVTX	monolithic active pixel sensor–based vertex detector

N

Nab	neutron “a” and “b” (experiment)
NAS	National Academy of Sciences
NCNR	NIST Center for Neutron Research
ND	University of Notre Dame
NDIAWG	Nuclear Data Interagency Working Group
nEDM	neutron electric dipole moment
nEXO	next-generation Enriched Xenon Observatory
NEXT	Neutrino Experiment with a Xenon TPC
NICER	Neutron Star Composition Explorer 1
NIF	National Ignition Facility
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NNDC	National Nuclear Data Center
NNSA	National Nuclear Security Administration
NPDGamma	(experiment)
NSAC	Nuclear Science Advisory Committee
NSAC-ND	NSAC Nuclear Data (subcommittee)
NSCL	National Superconducting Cyclotron Laboratory
NSF	National Science Foundation
NSRL	NASA Space Radiation Laboratory
NTNP	Nuclear Theory for New Physics (collaboration)
nuCARIBU	neutron-generator upgrade to CARIBU
NuPECC	Nuclear Physics European Collaboration Committee
NuSea	(experiment)
NUSTAR	Nuclear Structure, Astrophysics, and Reactions

O

ORNL	Oak Ridge National Laboratory
OU	Ohio University

P

PDF	parton distribution function
PEN	(experiment)
PET	positron emission tomography
PFAS	polyfluoroalkyl substances
PHENIX	Pioneering High Energy Nuclear Interaction Experiment
PiBeta	(experiment)
PiENu	(experiment)
PIER	Promoting Inclusive and Equitable Research
PIGE	particle-induced gamma-ray emission
PIONEER	(experiment)
PIXE	proton-induced x-ray emission
pNab	upgrade to Nab experiment
PRad	(experiment)
PRad-II	(experiment)
PREX	Lead (Pb) Radius Experiment
PSI	Paul Scherrer Institut
PSMA	prostate-specific membrane antigen
PVDIS	parity-violating deep inelastic scattering
PVES	parity-violating electron scattering

Q

QCD	quantum chromodynamics
QCS	quantum computing and simulation
QGP	quark–gluon plasma
QGT	(collaboration)
QIST	quantum information science and technology
QSe	quantum sensing

R

RAISOR	In-Flight Radioactive Ion Separator
RDK	(experiment)
ReA	re-accelerator
RENEW	Reaching a New Energy Sciences Workforce
RESOLUT	Resonator Solenoid with Upscale Transmission
RESONEUT	neutron array at RESOLUT
REU	Research Experience for Undergraduates
RF	radio frequency
RHIC	Relativistic Heavy Ion Collider
RIB	rare-isotope beam
RIBF	Radioactive Isotope Beam Factory

RIKEN	Institute of Physical and Chemical Research (Japan)
RILAC	(instrument)
RT	radiotherapy

S

SAMURAI	Superconducting Analyzer for Multi-Particles from Radioisotope Beams
SBIR	Small Business Innovation Research
SBS	Super BigBite Spectrometer
SciDAC	Scientific Discovery through Advanced Computing
SeaQuest	(experiment)
SEE	single-event error
SEU	single-event upset
SHMS	Super High Momentum Spectrometer
SIDIS	semi-inclusive deep inelastic scattering
SiPM	silicon photomultiplier
SLAC	SLAC National Accelerator Laboratory
SNO	Sudbury Neutrino Observatory
SNS	Spallation Neutron Source
SoLID	Solenoidal Large Intensity Device
SPECT	single-photon emission computed tomography
sPHENIX	Super Pioneering High Energy Nuclear Interaction Experiment
SRC	short-range correlation
SRF	superconducting radio frequency
STAR	Solenoidal Tracker at RHIC
STTR	Small Business Technology Transfer
SULI	Science Undergraduate Laboratory Internships
SuperKEKB	an asymmetric energy electron–positron Super B factory in Japan
SURF	Sanford Underground Research Facility

T

TAMU	Texas A&M University
TMD	transverse-momentum-dependent parton distribution function
TOF	time of flight
TPC	time-projection chamber
TRINAT	(instrument)
TriSol	triple solenoid (beamline)
TRISTAN	Tritium Sterile Anti-Neutrino (detector)
TRIUMF	Canada's Particle Accelerator Centre
TUNL	Triangle Universities Nuclear Laboratory

U

UCN	ultracold neutron
UCNA	Ultracold Neutron Asymmetry (experiment)
UCNProbe	Ultracold Neutron Probe (experiment)
UHECR	ultrahigh-energy cosmic rays
UK	University of Kentucky
UML	University of Massechusetts at Lowell
USNDP	US Nuclear Data Program
USQCD	US Lattice Quantum Chromodynamics (collaboration)
UW	University of Washington

V

VENUS	Versatile Electron Cyclotron Resonance Ion Source for Nuclear Science

W

W/SciFi	tungsten scintillating fiber
WANDA	Workshops for Applied Nuclear Data

X

XRB	x-ray burst

1 EXECUTIVE SUMMARY

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

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

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

1.1 LONG RANGE PLAN PROCESS AND HISTORY

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

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

1.2 THE SCIENCE QUESTIONS

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

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

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

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

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

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

Here are the recommendations of the 2023 Long Range Plan.

RECOMMENDATION 1

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

This recommendation requires

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

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

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

RECOMMENDATION 2

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

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

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

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

RECOMMENDATION 3

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

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

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

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

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

RECOMMENDATION 4

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

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

1.3 STRATEGIC OPPORTUNITIES

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

1.3.1. Opportunities to advance discovery

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

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

1.3.2. Cross-cutting opportunities

1.3.2.1. Emerging technologies: computing and sensing

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

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

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

1.3.2.2. Multidisciplinary centers

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

1.3.2.3. Nuclear data

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

1.4 INTERAGENCY COORDINATION AND COLLABORATION

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

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

1.5 WORKFORCE

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

1.6 SYNERGIES WITH OTHER RESEARCH DISCIPLINES

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

1.7 INTERNATIONAL COORDINATION AND COLLABORATION

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

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

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

1.8 RESOURCES

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

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

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

1.9 THE PAGES AHEAD

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

2

NUCLEAR SCIENCE: OVERVIEW AND IMPACT

More than a century ago, Ernest Rutherford discovered the atomic nucleus, a dense core at the center of the atom containing almost all its mass but occupying just a tiny fraction of its volume. At the time, it was assumed that the constituents of the atomic nucleus were protons and electrons. In 1932, James Chadwick invalidated this picture by discovering the neutron, a neutral particle with a mass comparable to that of the proton. Only 3 years later, Hans Bethe and others developed the first theoretical model of the atomic nucleus. The field of nuclear physics was born.

2.1 NUCLEAR PHYSICS TODAY

In the intervening years, nuclear physics has grown into a vibrant scientific discipline that would be unrecognizable to the originators of the field. Nuclear science has become a complex field, requiring exploration of matter from the tiniest subatomic particles to large astrophysical objects, and with a broad range of energies and tools. By invoking all the forces of nature—gravity, electromagnetism, and the strong and weak nuclear forces—the nuclear physics community aims to explain the nature of matter, its interactions, the emergence of structure, and its impact on the fabric of the cosmos.

Nuclear science encompasses four broad and interconnected subfields that are discussed in the next few chapters.

- Quantum Chromodynamics—We investigate the strong nuclear force described by quantum chromodynamics (Chapter 3) to learn how protons and neutrons emerge from their basic quark and gluon constituents. Our highest priority for new facility construction is the EIC that will finally enable us to study the remarkable properties of the gluons that connect quarks and hold the key to the enormous energy in the nucleus.

- Nuclear Structure and Nuclear Reactions—The nuclear structure and nuclear reactions subfield (Chapter 4) involves investigating how protons and neutrons serve as the building blocks for thousands of nuclear isotopes, what limits the number of protons or neutrons a nucleus may contain, and what reactions are possible among nuclei. Nuclear collisions, fission, fusion, and decay are complex processes involving both the strong and weak nuclear forces.

- Nuclear Astrophysics—The nuclear astrophysics subfield (Chapter 5) includes the study of nuclear processes that are relevant to astrophysical phenomena—including the birth, life, and death of stars—in which chemical elements are forged. This subfield includes exciting connections to the field of astrophysics: members of our community are part of interdisciplinary teams that seek to understand exotic aspects of our universe, such as neutron star mergers and supernovae.

- Fundamental Symmetries—In the fundamental symmetries subfield (Chapter 6), we use the vast nuclear landscape as a unique laboratory to study some of the deepest mysteries in the universe, such as why we live in a universe that is entirely made from matter (as opposed to antimatter). This subfield involves experiments to investigate the weak nuclear force and to elucidate the nature of neutrinos and other fundamental particles. Our highest priority for new experiment construction is to launch a campaign of neutrinoless double beta decay experiments, the results of which would have profound implications for our understanding of matter.

2.2 THE INTERPLAY BETWEEN FACILITIES, RESEARCHERS, AND PROJECTS

Nuclear science research is performed in the United States by researchers who use a network of university and national laboratory facilities. The nature of this science requires accelerators with a wide range of energies. Large and highly complex facilities are necessary to accelerate subatomic particles—such as electrons, protons, and heavy ions—to high enough energies to enable probing the tiniest substructure of matter and to advance our understanding of the strong and weak nuclear forces. Some of these powerful accelerators experimentally recreate the conditions present in the early universe and inside stars. Large user facilities built over many years enable the research programs of thousands of scientists and include the current ATLAS at Argonne National Laboratory (Argonne), CEBAF at Jefferson Lab, FRIB at Michigan State University, RHIC at BNL, and the planned EIC at BNL. In addition to the large facilities, our field exploits lower energy, smaller accelerator laboratories, each offering unique beam, instrumentation, and detector capabilities, at thirteen universities and Lawrence Berkeley National Laboratory (LBNL). Chapter 9 provides an overview of the nuclear facilities.

These facilities are used by thousands of researchers distributed across the country at US universities and national laboratories and by scientists from all over the world. A university nuclear physics research group may range from a single faculty member and graduate students to several faculty along with postdocs, graduate students, and sometimes technical support staff. Most faculty incorporate undergraduates into their group, providing those students with valuable training and experience. Similar research groups exist at national laboratories, although the students come from universities. Research groups can be experimental, theoretical, or a mix of both. The experimentalists design and construct novel detectors, plan and implement new experiments, analyze data, and present results to the community for discussion. Critical to realizing the full fruits of the experimental efforts are the theorists (Chapter 7), who explain the phenomena that underlie the experimental data, connect and predict results across subfields—and even across disciplines—and provide insights that lead to new directions for nuclear science.

In addition to the traditional categories of theory and experiment, computational nuclear physics has established itself as an essential third modality for nuclear research. Computational nuclear physics overlaps with theoretical and experimental research and connects to cross-cutting tools such as machine learning (ML) and artificial intelligence (AI). New experiments stimulate the development of major theoretical and computational advances that, in turn, uncover new mysteries that motivate additional experiments. Synergistic interactions among all types of researchers enables nuclear science to advance and respond expeditiously to challenges emerging from new discoveries.

Funding for nuclear science comes primarily from DOE SC and NSF to support research, operate user facilities, and manage projects. Projects can involve building new facilities such as the EIC, constructing significant new experiments such as neutrinoless double beta decay, developing new detectors, or upgrading accelerators. Research funding is crucial because it enables the people at the heart of nuclear science to execute the exciting program described in this Long Range Plan. Funding for facility operations is critical to maximizing our return on investment, enabling as many experiments as possible. The nuclear physics community recognizes that all three areas (facility operations, research, and projects) must be healthy to maintain US leadership in nuclear science and to set the stage for tomorrow's discoveries.

2.3 CONNECTIONS TO OTHER FIELDS

Because nuclear science spans such a wide range of phenomena—from the inside of the proton to collisions between neutron stars—the field provides fundamental and lasting connections to many other scientific endeavors, such as astrophysics, atomic physics, condensed-matter physics, accelerator science, particle physics, and fusion energy science. Transformational ideas that often see application in other areas of science have been spawned from successful collaborative efforts that bring scientists together within and across disciplinary boundaries. Examples include the Joint Institute for Nuclear Astrophysics, the Institute for Nuclear Theory (INT), and the theoretical topical collaborations. The synergies between nuclear science and other fields are presented in the various science sections of this Long Range Plan.

The impact of nuclear science extends to technical fields as well. High-performance computing (HPC) and ML techniques have led to key advances in nuclear physics. Conversely, nuclear science routinely pushes the limits of these fields because of the technical requirements of our experimental and theoretical pursuits. We have a long tradition of educating students in the most advanced technologies. In fact, much of the experimental and theoretical work described herein is executed by students, many of whom take their cutting-edge skills and knowledge—such as AI, detector technologies, simulations, or quantum computing and sensing—to industry. Chapter 10 describes some of these cross-cutting technologies.

Attracting and retaining junior scientists is a very high priority for nuclear science (Chapter 8). Graduate researchers provide critical support for experimental, theoretical, and computational efforts, even as they learn the science and master the relevant techniques. By the time they have completed their studies, they have transitioned from novices to independent researchers, capable of pushing the field in new and exciting directions. Graduate students form a foundational component of the nuclear physics workforce, so they are typically remunerated to allow them to focus on supporting their experiments or driving the theory forward with the understanding that they are exclusively devoted to the task. Unfortunately, this remuneration is frequently insufficient to meet their basic needs. Addressing this pay gap is a key priority for our community, as is reducing other barriers to participation in nuclear science.

2.4 BENEFITS FOR THE NATION

While pursuing a science agenda that addresses questions about matter and the universe, nuclear physics delivers many applications and benefits to society. Scientific discoveries enhance our fundamental understanding of nature, making new applications possible. The technologies we develop to do the science, such as cutting-edge detectors, often lead quickly to new uses. The skills and training our students receive are needed in many critical areas such as isotope production and national security (Sidebar 2.1). The scientific enterprise is fertile ground for producing innovators and entrepreneurs. In short, nuclear physics provides the foundational knowledge and technology required to manipulate matter and the vast amounts of energy therein. Examples are included throughout this report, particularly in Chapter 11. The following subsections briefly describe a few key applications in the areas of medicine, energy production, and national security.

2.4.1. Nuclear physics and medicine

Since Wilhelm Röntgen's discovery of x-rays in 1895, basic physics research has provided indispensable methods for medical diagnostics and treatment. Technology made possible by nuclear physics has enabled medical researchers and practitioners to peer inside the living human body and create vivid and highly detailed 2D and 3D images that are used to diagnose injuries and illness, locate and manage cancer, and monitor organ function. Radiation therapy can deliver precise, targeted doses to malignant tumors, without surgery, to eliminate cancerous bodies. Following are just a few examples:

- Nuclei that emit alpha particles have been shown to cure metastatic cancer in previously untreatable patients.
- Positron emission tomography (PET) employs radioactive isotopes to produce 3D images of internal organs and structures when x-rays cannot provide sufficient contrast. PET imaging is crucial for diagnosing and monitoring cancer, neurological disorders, and cardiovascular diseases.
- Single-photon emission computed tomography (SPECT) uses gamma-emitting isotopes to create detailed images of internal organs and tissues.
- The metastable nuclear isomer technetium-99m is used in tens of millions of medical diagnostic procedures annually. It is used as a radioactive tracer to provide vital information about organ structure, blood flow, and abnormal tissue growth.
- In brachytherapy, tiny radioactive sources are implanted inside or near a cancerous tumor to deposit a highly localized dose that kills cancer cells while minimizing damage to surrounding healthy tissue.
- External radiation therapy, using beams of high-energy gamma rays or protons, can provide a targeted dose to eliminate otherwise inoperable tumors in the brain or eye.

Technology discovered through basic nuclear physics research assists accurate diagnoses, enables targeted therapies, and saves many lives. Continued advancements in nuclear physics will provide new possibilities for the future of medicine.

2.4.2. Clean energy

US government investment in nuclear physics was born of necessity during a time of war. Enrico Fermi constructed the first critical nuclear pile at the University of Chicago in 1942, unleashing the power of nuclear fission to produce energy. Since then, nuclear power has produced reliable, safe energy with far lower risk to health than the other predominant sources of electricity in the United States. Reliable, baseline power from nuclear energy together with the development of renewable energy may be the best chance to address climate change by limiting the release of greenhouse gases. Today in the United States, nuclear energy produces nearly 20% of the needed electricity and contributes 55% of the carbon-free energy portfolio. These numbers must increase significantly if clean energy objectives are to be met.

The nuclear energy field is undergoing rapid expansion: more than a dozen private-sector startup companies are pioneering a new class of inherently safe, proliferation-resistant, small modular reactors. The development of these reactors, which feature novel fuels and use a broader range of neutron energies, requires a wide range of data: fission product yields, reaction cross sections, decay data, and more. Only the nuclear science community can deliver those data.

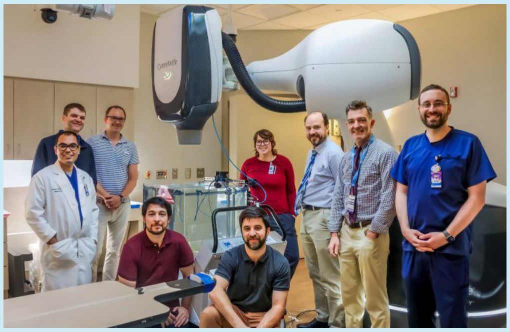
In addition to proven fission power technology, nuclear fusion holds the promise of producing energy free from the complications of long-term spent fuel storage. Nuclear science provides diagnostic techniques that play a key role in defining the conditions in the high energy density plasma needed to achieve energy breakeven. The world marveled when it was announced in 2022 that the National Ignition Facility at Lawrence Livermore National Laboratory achieved fusion ignition—for a brief time the energy produced exceeded the input energy needed to produce the reaction.

Sidebar 2.1 Profiles in Versatility

While the nuclear physics enterprise trains students and early career researchers to perform cutting edge research, those skills are highly transferable. Students from nuclear science can be found in many different places, supporting American innovation.

Name: Gopal Subedi
Hometown: Atlanta, Georgia
Undergraduate school: Colby College (Waterville, Maine)
Graduate School: Purdue University (West Lafayette, Indiana)
Current position: Medical physicist

"I came to know of the medical physics field after talking to a health physicist at Texas A&M University and to other Research Experience for Undergraduates participants. These conversations eventually led me to apply to a medical physics graduate program. Medical physics is a good blend of medicine and technology. We treat cancer patients with radiation, so it is very rewarding. A medical physicist (also often referred to as radiation oncology physicist) has to have a clear understanding of basic nuclear science. As clinicians, we have a major role in safe and accurate delivery of radiation to our patients."



Gopal with fellow physicists and engineers posing with the Cyberknife, a robotic radiosurgery system used for radiation treatments [S1]

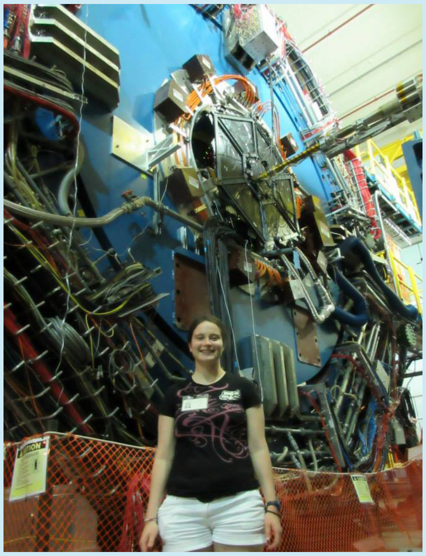
Name: Johnny Cesaretto
Hometown: Cleveland, Ohio
Undergraduate school: John Carroll University (Cleveland, Ohio)
Graduate school: UNC Chapel Hill (Chapel Hill, North Carolina)
Current position: Senior Optical Engineer, Amazon

[S2]

"I had the tremendous opportunity to participate in the Research Experience for Undergraduates at Triangle Universities Nuclear Laboratory during the summer. This was the catalyst that started my career as a scientist and engineer. The skills developed in troubleshooting; failure and root-cause analysis; testing hypotheses; coding; designing instrumentation; experiment planning; building, tearing down, revising, and building again; and persistently approaching complex problems from multiple angles and across a broad application space have made me the scientist and engineer I am today. The skills I developed pursuing research in nuclear science are still very much a part of the way I have approached and solved problems in industry."

Name: Kathryn Meehan
Undergraduate school: Haverford College (Haverford, Pennsylvania)
Graduate school: UC Davis (Davis, California)
Current position: Senior data scientist, First American Title Insurance Company

"I love my current job, and one of the reasons I find it rewarding is that I get to use the skills I learned from nuclear physics research every day! On a typical day, I dive into data analysis and build statistical and machine learning models to predict risk and streamline the customer experience. My physics background gave me a respect for knowing my data set intimately and understanding the biases and limits of the collection method. This is an important perspective to bring to industry where most problems are limited by the quality of the data as opposed to the sophistication of the algorithm applied to the data."



Kathryn stands in front of the Solenoidal Tracker at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory [S3]

[S4]

Name: Andrew Zarella
Undergraduate school: Florida State University (Tallahassee, Florida)
Graduate School: Texas A&M University (College Station, Texas)
Current position: CMP data scientist, Intel

"The skills I developed in my nuclear science degree are invaluable to my current career. I find that I entered my career significantly ahead of most of my peers with respect to the ability to operate independently and efficiently and to employ data-driven decision-making. I always felt safe and free to be myself among my peers in the nuclear science community."

Name: Eden Reynolds
Undergraduate school: West Virginia Wesleyan College (Buckhannon, West Virginia)
Current position: McCuskey Fellow

"This year I will be a senior in the Applied Physics Program at Wesleyan. Currently this summer, I have been studying the hyperfine energies of the rubidium and cesium atoms and the role of the nucleus in the resulting spectra. Specifically, I am interested in applying the Maria Goeppert-Mayer shell model to the data that I am acquiring. And, there are some really practical applications for this type of research. It is very important in optical, atomic, and nuclear physics, and in engineering. It is a very important field to pursue."

[S5]

2.4.3. National security

Nuclear science contributes in many ways to national and international security. Two examples are maintaining the safety and reliability of the US nuclear stockpile and working with international partners to slow or stop the illicit spread of nuclear weapons to other countries and non-state actors. The NSAC nuclear data reports spelled out the importance of cutting-edge nuclear science research for stewardship science and nonproliferation. The National Nuclear Security Administration (NNSA) Office of Defense Nuclear Nonproliferation has partnered with DOE NP to help co-organize an annual series of workshops (WANDA) that identify outstanding national security–related nuclear data needs and develop a collaborative plan to address them through targeted measurements, modeling, and evaluation. The "National Security" and "Nonproliferation" sections of the first NSAC report also highlight the critical need for a well-trained workforce, pointing to a host of traineeship programs such as the Defense Program Stewardship Science Academic Alliance Program and the four Nonproliferation Research and Development nuclear security consortia. These programs train hundreds of graduate students throughout the United States at DOE NP facilities in nuclear science and engineering. The nuclear science community also develops detectors with security applications (from portal monitors to satellite-based detection of nuclear detonation).

In summary, nuclear physics addresses the fundamental science questions of our time, produces a workforce that addresses critical national needs, provides synergies with other fields of science and technology, and enables high-impact applications that benefit society. Our accomplishments and plans for the future are detailed in this Long Range Plan for nuclear science.

3 QUARKS AND GLUONS: UNDERSTANDING THE STRONG NUCLEAR FORCE

3.1 OVERVIEW

The quest to understand the nature of matter and the nucleus of the atom begins with quarks and gluons. These elementary particles are the building blocks of protons and neutrons, which in turn form nuclei, from hydrogen to the heavy elements (such as uranium or lead). The four basic forces of nature—gravitational, electromagnetic, strong, and weak—govern how objects or particles interact and how particles decay.

The strong nuclear force governs the interactions between quarks and gluons (collectively known as partons) and is described by the theory of quantum chromodynamics (QCD). One remarkable feature of QCD is that the force between quarks is small at close distances but grows larger as the quarks separate. This force is very different from gravity or electromagnetism; the force between two massive objects such as stars grows weaker with distance, as does the force between positive and negative charges. QCD is a complex force with three color charges (labeled red, green, and blue). Protons and neutrons are each composed of three valence quarks, one of each color, to form a colorless object. Gluons are exchanged between the three quarks and carry the strong nuclear force. Gluons can interact not only with quarks but also with each other, leading to interesting consequences. Adding to the complexity are the sea quarks, which are quark–antiquark pairs that are created and destroyed on very short time scales. Quarks come in six flavors: up and down—the valence quarks in the proton and neutron—and four heavier quarks (strange, charm, bottom, and top), some of which can form other, shorter-lived hadrons.

In the United States, QCD is studied experimentally using electron beams at CEBAF at Jefferson Lab and using proton and heavy ion beams at the RHIC accelerator at BNL. During the next few years, we anticipate that RHIC operations will be completed and the EIC will be built at BNL. Relating the underlying theory of QCD to observable matter requires theoretical research employing myriad approaches. Theoretical calculations are often heavily computational because of the complexity of QCD.

The primary goal of the QCD subfield of nuclear science is to understand the properties of nuclear matter in terms of pointlike quarks and gluons. Quarks, antiquarks, and gluons form particles known as hadrons. The proton and neutron are the most familiar and ubiquitous hadrons in nature. Other shorter-lived hadrons, including mesons such as the pion, illustrate the varied ways in which QCD manifests in nature. At high temperature and pressure, quarks and gluons are not confined to hadrons and instead form a quark–gluon plasma (QGP), a state of matter discovered at RHIC. Jefferson Lab and RHIC provide the intense beams and complex instrumentation necessary to study the proton's internal substructure and the QGP.

Since the last Long Range Plan, we have made great progress in understanding the fundamental structure of the nucleon, including many aspects of its size and structure, although new questions have emerged. The QGP has been studied using jets (collimated sprays of detected particles), and significant advances have been made in quantifying the reduction in energy when jets interact with the QGP. Measurements at both RHIC and the Large Hadron Collider (LHC) have provided new insights on the QGP using heavy quark and electromagnetic probes. First-principles QCD calculations using the world's most powerful computers have become and continue to be increasingly important in understanding the spectrum, structure, and interactions of hadrons as well as the behavior of QCD at nonzero temperature.

Even with our impressive progress in understanding QCD, today's tools are insufficient to answer fundamental questions related to the role of gluons within protons, neutrons, and nuclei. As scientists examine protons and neutrons more and more closely, the important role of gluons in hadron and nuclear structure is becoming increasingly apparent. Furthermore, understanding how the QGP forms when two nuclei collide is thought to be connected to understanding how a large number of gluons within a single nucleus can act in concert, like a classical wave rather than as many individual particles. A complete understanding of how protons and nuclei are built and of how the QGP forms will require a powerful new experimental facility: the EIC.

The EIC will make it possible to resolve the gluon and sea quark structure of protons and nuclei with a precision comparable to that with which CEBAF maps their valence quark structure. The EIC will perform precise measurements to form a complete picture of how the proton's spin is generated by quarks and gluons. It will also explore how the interactions among gluons themselves serve to prevent the numerous gluons deep in the heart of nuclei from building up arbitrarily dense states. These explorations, together with theoretical advances, will help us explain how a theory encapsulated by a few seemingly simple equations can generate the observed complexity of nuclear matter.

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

The EIC particle accelerator technology builds on considerable existing expertise both at CEBAF and RHIC, pushes beyond the state of the art, and will put the United States at the frontier of accelerator technology worldwide. The EIC detectors and scientific instrumentation are essential to fully exploit the exciting scientific opportunities ahead and will require significant investments.

In this chapter, we examine the many achievements since the 2015 Long Range Plan, describe the future exciting science planned with existing facilities, and look ahead to the discovery potential of the EIC.

3.2 THE FUNDAMENTAL STRUCTURE OF VISIBLE MATTER

Protons and neutrons, known as nucleons, are composed of nearly massless quarks and massless gluons, yet as the building blocks of atomic nuclei they make up essentially all the visible mass in the universe. In ways that remain deeply mysterious, their mass and other properties emerge from the strong interactions of their fast-moving constituents.

Many experiments at high-energy electron scattering accelerators (e.g., Jefferson Lab and the future EIC) focus on a process called deep inelastic scattering (DIS), in which an electron probe interacts with a constituent of the nucleon, such as a single quark. Information about the structure of the nucleon is obtained by measuring the likelihood of this process as a function of two quantities. The first is the spatial resolution with which the nucleon substructure is examined. At high resolution, new phenomena come into focus, such as the possibility that a quark radiates or absorbs a gluon or that gluons produce quark–antiquark pairs. Obtaining high resolution requires transferring large momentum to the nucleon constituent (small wavelengths). Results are often presented as a function of the quantity Q^2, which is the square of the momentum exchanged between the probe and the target.

The second important quantity for understanding DIS interactions is related to the nucleon constituent that is probed. The fraction of the total momentum of the target nucleon that is carried by that constituent is known simply as x. DIS experiments have established a basic picture of the nucleon in which, at low resolution, the nucleon comprises three valence quarks. For example, the proton has two up (u) quarks and one down (d) quark. These valence quarks carry a large fraction of the proton's momentum and typically have x values between 0.1 and 0.8. The large energy in the interactions between quarks also gives rise to large numbers of quark–antiquark pairs (known as sea quarks) and gluons, which become visible with increasing resolution. These extra constituents dominate the small-x regime, which can extend to as low as 10^{-4} at the EIC.

Figure 3.1 is an artistic rendering of the nucleon corresponding to three different values of the momentum fraction (x) carried by quarks inside. The largest x value (left) represents the dominance of three valence quarks, and the smallest x value (right) shows the gluon-rich region. A complete understanding of the complex and dynamic internal structure of the nucleon within the underlying theory of QCD is central to the study of visible matter. One reason why quarks and gluons are so difficult to study experimentally is that they cannot be accessed in isolation. They are always bound inside hadrons, a phenomenon known as color confinement, which is a fundamental property of QCD.

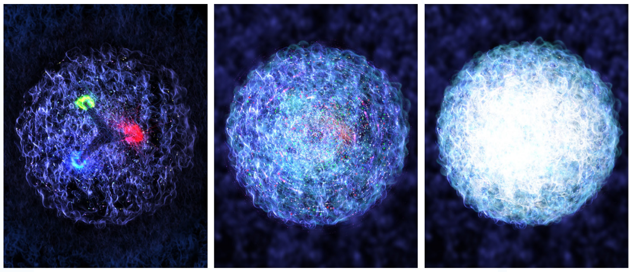


Figure 3.1. An artistic rendering of the nucleon with three different values of the momentum fraction of the quarks inside the nucleon.*The x value goes from (left) the largest to (right) the smallest, matching the focus of Jefferson Lab at high x and the future EIC from medium to low x [1].*

Since the 2015 NSAC Long Range Plan, many exciting results in hadron physics research have been achieved by facilities in the United States and worldwide, including

- A new and innovative measurement of the proton's charge radius,
- Extraction of pressure distribution inside the proton,
- Measurements of intriguing quark momentum distributions, both in the nucleon and when bound in a nucleus,
- First measurements of the gluon spin contribution to the spin of the proton,
- Measurements of the correlation between the

direction of the proton's spin and the motion and spin of the quarks inside it.

- Observation and discovery of new and exotic hadronic states, including new XYZP states.
- Evidence for having very tightly correlated nucleon pairs inside a nucleus.

These results have advanced our understanding of static properties of the nucleon, its quark and gluon structure, and its properties when embedded in a nucleus. These achievements have not only tested QCD's fundamental properties, predicting new hadronic states and probing the 3D structure of the nucleon, but also stimulated deeper questions about QCD and hadron physics. For example,

- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

The proton and all other hadrons are not elementary particles—they have a complex internal structure of quarks and gluons, the dynamics of which are responsible for the observed properties of these hadrons, including their masses, spins, magnetic moments, and their responses to external forces. A deeper understanding of hadrons, their formation, and their properties requires that we understand and quantify their internal structure in terms of the constituents. Addressing these fundamental questions requires theoretical progress and experimental investigation at major facilities.

The following subsections highlight some of the recent accomplishments since the 2015 Long Range Plan along with future opportunities to address these fundamental questions. We focus first on how valence quarks influence proton and neutron properties.

3.2.1. How big is the proton?

The simplest characterization of the distribution of charge within the proton is the charge radius, r_p, effectively the proton size. The value of r_p has broad impacts across nuclear, atomic, and particle physics. Consistent r_p values were extracted from accelerator-based electron scattering and tabletop atomic hydrogen experiments, but a puzzle arose in 2010 when an experiment at the Paul Scherrer Institute (PSI) extracted a significantly discrepant value from a precision measurement of energy-level transitions that is highly sensitive to proton size in muonic hydrogen, a hydrogen atom with a muon in place of the electron. According to the Standard Model of particle physics, muons are particles that should behave exactly like heavy electrons, so any discrepancy may indicate the possibility of brand new physics. Since the last Long Range Plan, the PRad electron–proton scattering experiment at Jefferson Lab implemented several innovations to obtain a new r_p value that agreed with the muonic hydrogen results. A follow-up experiment, PRad-II, is being planned, aiming for a factor of four improvement in precision, addressing the question of whether the electron and the muon experience the proton charge radius differently. International experiments are running or planned, including the US-led Muon Proton Scattering Experiment (MUSE) at PSI, whose primary goal is to determine r_p from muon–proton scattering.

A more detailed characterization of the distribution of charges and currents in the nucleon is provided by the electric and magnetic form factors, which are extracted from measurements of elastic electron–nucleon scattering, and these measurements remain a core component of the Jefferson Lab 12 GeV science program, particularly using the Super BigBite Spectrometer (SBS). Understanding the behavior of charge and current distributions at higher spatial resolution or Q^2 (at distances much smaller than r_p) is a priority because theoretical predictions differ. The precision of the form factor determinations is limited by the conventional assumption that the scattering process is described by the exchange of a single mediator photon. The role of two-photon exchange can be determined by measurements using a positron beam, which could be realized at Jefferson Lab with a modest accelerator upgrade.

Just as a magnetic material responds to being exposed to a magnetic field by undergoing internal rearrangement, so can the polarizability of a nucleon be measured by exposing it to an electromagnetic field in the Compton scattering process. Since the last Long Range Plan, we have seen the first extraction of the proton spin polarizabilities from measurements at the Mainz Microtron (MAMI) accelerator and results on various nucleon polarizabilities from Jefferson Lab and the High Intensity Gamma-Ray Source (HIGS) at Triangle Universities Nuclear Laboratory (TUNL). These measurements test theoretical predictions using lattice QCD and chiral effective field theory, a low-energy description of QCD.

Unlike the proton charge radius, no direct methods exist for probing the proton's matter distribution, which is dominated by the electrically neutral gluons. Innovative indirect approaches to probe the gluons have been proposed, based upon their coupling to spatially compact heavy quark–antiquark bound states. Recent first measurements of production of a charm–anticharm bound state at Jefferson Lab suggest that the matter radius appears to be smaller than the charge radius. More detailed measurements are planned, and eventually we will be able to access gluons by detecting the production of heavier bottom–antibottom bound states at the EIC.

3.2.2. How are quarks distributed in the nucleon?

The momentum of quarks and gluons (which are both partons) inside the proton can be studied using the DIS process, introduced above. Parton distribution functions (PDF) describe the likelihood of finding a parton in the nucleon as a function of that parton's momentum fraction (*x*). At Jefferson Lab, DIS experiments primarily probe valence quarks; data in the valence regime can directly test fundamental theoretical predictions. The ratio of the distribution of down to up quarks in the proton *d*(*x*)/*u*(*x*) is of particular interest and has been measured by three experiments (MARATHON, BONuS12, and Hall C). The MARATHON experiment measured the tritium/helium-3 DIS cross section ratio, thus comparing the proton (uud) with the neutron (udd). From there, the ratio of the neutron-to-proton structure function, which is related to the distribution of all the quarks in the nucleon, is extracted. That ratio is sensitive to *d/u* and is shown in Figure 3.2(top) as a function of *x*. The new results from MARATHON show the ratio leveling off between 0.4 and 0.5 as *x* increases to 1, consistent with the value predicted by QCD of 3/7. The BONuS12 experiment, which uses a novel technique to measure DIS from an effectively free neutron target, will soon publish results for the same ratio. A model-independent extraction of the ratio in Figure 3.2 can also be obtained in parity-violating DIS (PVDIS) with the proposed SoLID experiment at Jefferson Lab, where the strange-quark PDF in the valence regime can also be accessed.

It is also very interesting to measure the momentum distributions of the sea quarks (quark–antiquark pairs that are found predominantly at low *x*). Measurements of antiquark momenta are more difficult owing to the dominance of quarks over antiquarks in the nucleon. By measuring muon–antimuon pairs in hadron–hadron collisions at the Fermi National Accelerator Laboratory (Fermilab), the NuSea and SeaQuest experiments demonstrated that the antiquark distributions, *ū(x) and đ(x)*, do not have the same momentum distribution (Figure 3.2[bottom]). Complementary information on *ū(x) and đ(x)* has been obtained at RHIC in proton–proton collisions. Explaining the observed asymmetry of antimatter in the nucleon presents a challenge to be addressed by future theoretical and experimental efforts.

A large-scale theoretical effort, often referred to as global fitting, combines all relevant experimental data (DIS and other) with the theoretical formalism to determine the PDFs from the measured cross sections. Advanced computing, simulation, and statistical techniques have been used to reliably quantify the uncertainty (shown as the bands in Figure 3.2) in these extracted PDFs. Since the last Long Range Plan, it has become possible to compute PDFs directly from QCD using lattice QCD techniques (Sidebar 3.1).

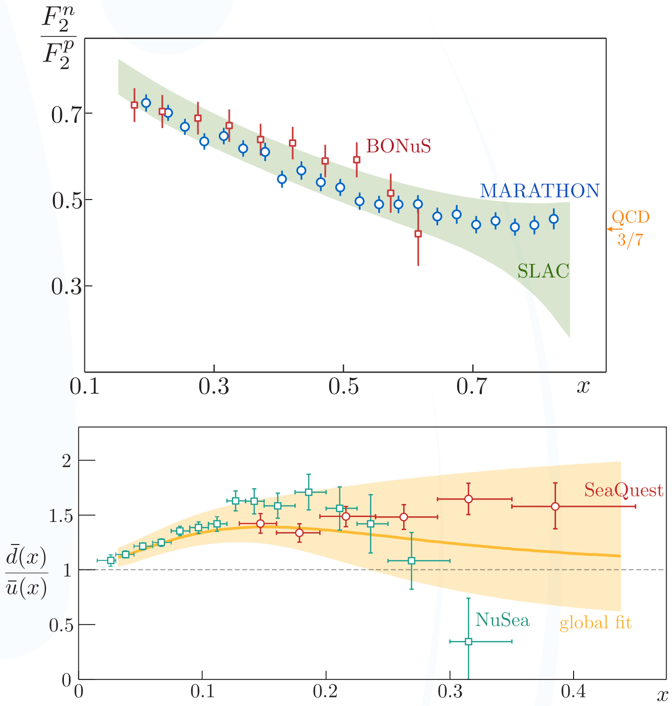


Figure 3.2. Measurements of quark and antiquark PDFs. *Top: The ratio of the neutron and proton structure functions plotted as a function of x from MARATHON, the 6 GeV BONuS experiment, and a global fit (green band) of previous SLAC data. Bottom: A plot of the ratio of antiquark distributions extracted from the SeaQuest experiment, compared with data from the E866/NuSea experiment at Fermilab and from a global fit (orange band) [2].*

3.2.3. Where does the proton spin come from?

In 1987 the European Muon Collaboration found that quark spins contribute surprisingly little to the proton spin. Understanding how the quark and gluon spins and their orbital angular momenta combine to make up the proton spin of 1/2 has become known as the proton spin puzzle. Significant progress has been made since the last Long Range Plan: the valence quark spin contribution was measured using polarized electron beams scattering off polarized proton and nuclear targets at Jefferson Lab. Antiquark contributions were sampled using weak boson production, and the contribution of gluon spin was accessed in polarized proton–proton collisions by the Solenoidal Tracker at RHIC (STAR) and the Pioneering High Energy Nuclear Interaction Experiment (PHENIX), indicating for the first time that gluon spins prefer to align in the same direction as the proton spin. Further investigation of the proton spin puzzle will be a major part of the EIC program and is discussed in greater detail in section 3.4.1.1.

3.2.4. Three-dimensional imaging of the proton

Nucleon femtography, the 3D imaging of the nucleon, is made possible by electron scattering measurements and has the potential to describe the nucleon's internal structure as completely as possible. Ultimately, the goal is to understand the position and momentum distributions of the constituent quarks and gluons in the nucleon. Such a complete picture will help elucidate the origin of the proton spin (Section 3.2.3), where lattice QCD calculations predict a significant contribution from the orbital angular momentum of the quarks and gluons to the proton spin. These 3D images are captured in two ways, as shown in Figure 3.3. First, the transverse spatial distributions of quarks and gluons are known as generalized parton distribution functions (GPDs). Second, the transverse-momentum-dependent parton distribution functions (TMDs) encode information on how the momentum of quarks and gluons are correlated with the parent hadron properties. Both sets of functions are measured in slices of the parton momentum fraction *x*, as illustrated in Figure 3.3. Extracting such pictures from measurements necessitates statistically precise data, which can be obtained at a high energy and intensity electron scattering facility using large-acceptance detectors.

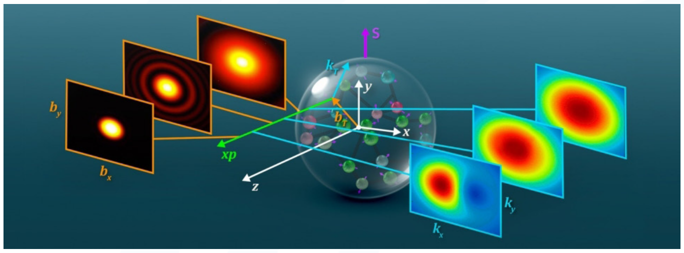


Figure 3.3. Parton images for a spin-up proton (magenta arrow) in slices of parton fractional momentum, x, for the quarks and gluons in a colliding hadron. *The images on the left give a spatial distribution in transverse location, while the images on the right picture the transverse momentum distribution [3].*

Spatial imaging. Spatial imaging techniques and GPDs not only provide information on the position distributions of quarks and gluons within the nucleon but also can provide information related to properties of the nucleon such as mass, angular momentum, pressure, and force distributions inside the nucleon (Sidebar 3.2). Pioneering measurements have been made since the last Long Range Plan, and a dedicated program has been launched at Jefferson Lab, including in Hall B with the CEBAF Large-Acceptance Spectrometer (CLAS)12 and in Hall C with the existing spectrometer and the new Neutral Particle Spectrometer), to study three complementary scattering processes in unprecedented detail and in coordination with theory. The possible addition of a polarized positron beam to CEBAF would enable precise separation of signal and background for one of the relevant processes to access GPDs. The future EIC will enable a complementary program to perform spatial imaging for quarks and gluons carrying smaller momentum fractions of the nucleon.

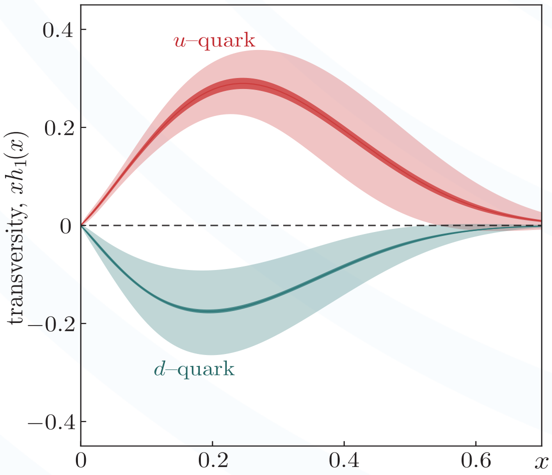


Figure 3.4. The up (red) and down (blue) quark transversity spin-spin correlation in the proton. *The wide uncertainty bands show the latest results based on a global fit to world data while the narrower, darker bands show the expected improvement by the SoLID detector [4].*

Transverse momentum imaging and spin–momentum and spin–spin correlations. Transverse-momentum imaging techniques, in conjunction with spin-dependent measurements, probe various spin–momentum correlations in the nucleon. These correlations are analogous to spin–orbit coupling effects in atomic systems. In addition to providing multidimensional images of quark and gluon momentum distributions within the nucleon, measurement of spin-momentum correlations in the nucleon can test our understanding of subtle aspects of QCD as a quantum field theory. Transverse spin–spin correlations are also of interest: the transversity distribution describes the difference in probability of scattering off of a transversely polarized quark in a transversely polarized proton where the quark spin direction is parallel or antiparallel to the proton spin direction. As shown in Figure 3.4, combining measurements from multiple recent experiments has revealed that the transverse spin of up quarks is more likely to be in the same direction as the proton spin, whereas that of down quarks is more likely to be in the opposite direction. The origin of these large and opposing spin–spin correlations is not yet understood. Proposed measurements at the Jefferson Lab SoLID detector and the future EIC will significantly improve our knowledge of these correlations. Transverse spin–spin correlations are also related to a property of the nucleon called the tensor charge, which can be calculated in lattice QCD. The tensor charge is linked to nucleon and quark electric dipole moments, which are sensitive to physics beyond the Standard Model.

Sidebar 3.1 Transformative Progress in Lattice QCD

Lattice QCD offers the only way to make rigorous predictions of the properties of hadrons from QCD. In the past 10 years, a combination of novel theoretical ideas and use of world-leading computation facilities has led to transformative progress that enables new areas of study for the spectrum, structure, and interactions of hadrons, as well as the behavior of QCD at nonzero temperature.

New techniques allow access within lattice QCD to the distribution of momentum of the quarks and gluons in a nucleon. Pioneering calculations have provided the first results (Figure 1), and the next stage is to obtain full control of systematic effects to allow comparison with distributions extracted from experimental data.

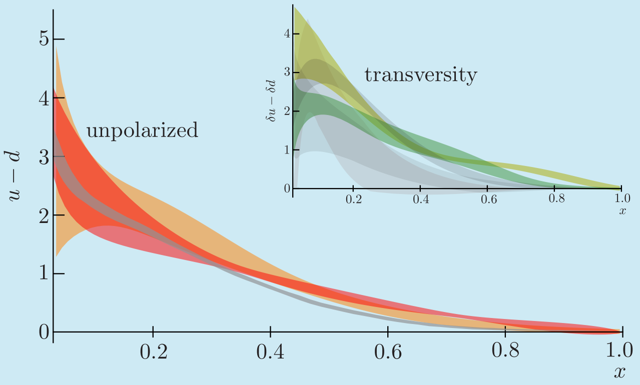


Figure 1. Unpolarized and transversity proton PDFs computed with lattice QCD (colored curves showing different pioneering approaches) compared to global fits to experimental data (grey curves) [S6].

The spectrum of excited hadrons can be studied by computing hadron–hadron scattering amplitudes, in which the hadrons appear as short-lived resonances (Figure 2). Recent calculations have moved from the simplest case of elastic scattering, where the resonance has only one possible decay mode, to coupled-channel scattering, where multiple final states are populated. Predictions for the preferred decay modes of exotic mesons are being used to guide current experiments.

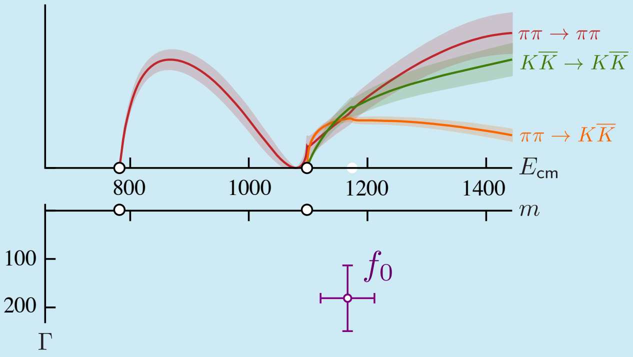


Figure 2. Coupled-channel scattering as a function of energy computed in lattice QCD showing how pion pairs can transform into kaon-antikaon pairs, enhanced by the presence of a resonant f_0 state whose mass and decay width are determined [S7].

Spin–momentum and spin–spin correlations in QCD can also be explored in the process of hadronization (Sidebar 3.3). Semi-inclusive DIS (SIDIS), in which a single hadron is detected from the fragments of the destroyed proton, allows access to these TMD distributions via asymmetries with respect to the spin when a transversely polarized proton is used as a target. The discovery of several nonzero spin–momentum correlations in the nucleon and in the process of hadronization by the HERMES experiment in Germany, the COMPASS experiment at CERN, and a Jefferson Lab experiment with a polarized helium-3 (effective polarized neutron) target established the importance of SIDIS for accessing TMD distributions and stimulated increased experimental and theoretical efforts. Polarized proton–proton collisions at RHIC have provided new insight on spin–momentum correlations, challenging some contemporary theoretical models, as illustrated in Figure 3.5, which shows measurements by the STAR collaboration of a nonzero spin–momentum correlation in hadron production in jets that is significantly larger than theoretical predictions. New data with forward upgraded STAR detector will further elucidate TMD physics and provide new insight. In the longer-term future, the EIC facility will undertake a comprehensive program to study spin–momentum and spin–spin correlations in nucleons and in the process of hadronization.

Lattice QCD can precisely determine the hadronic or nuclear matrix elements that might otherwise obscure observables sensitive to breaking of fundamental symmetries or new physics. A relevant example is the axial charge of the nucleon, which has recently been computed with controlled uncertainty at the level of 1% (Figure 3), illustrating techniques that are used to explore matrix elements of few-nucleon systems.

The ability to compute QCD at finite temperature has been used to obtain the heavy quark diffusion coefficient that describes the action of the quark–gluon plasma on a heavy quark. The results agree with expectations for the behavior of a perfect fluid (Figure 4) and provide a vital ingredient in the interpretation of experiments measuring the flow of heavy-flavor hadrons in heavy ion collisions.

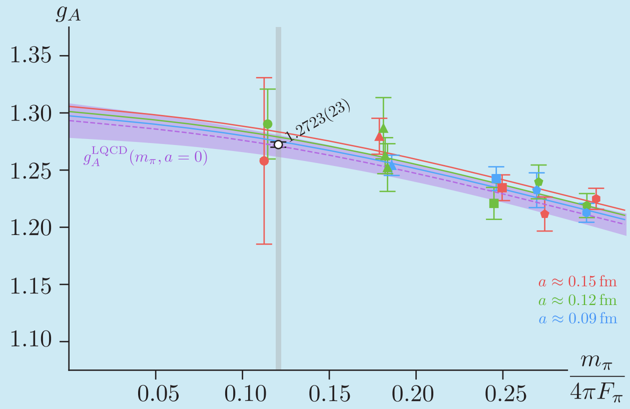


Figure 3. Precise physical-point determination of the nucleon axial coupling from lattice QCD extrapolated from non-zero lattice spacings, a, and unphysical pion masses [S8].

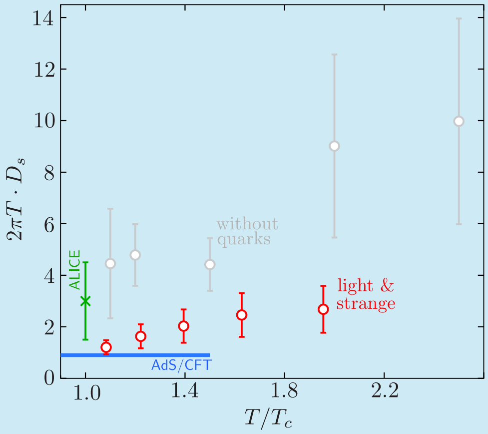


Figure 4. Heavy-quark diffusion as a function of temperature computed in lattice QCD (open circles) showing the effect of the presence of lighter quarks, and agreement with experimental data at the critical point [S9].

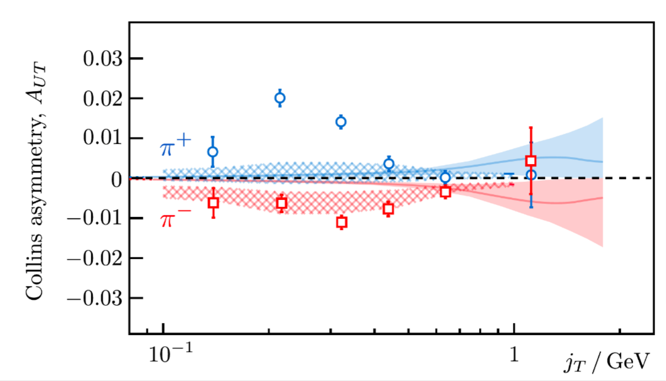


Figure 3.5. Measurements by the STAR experiment at RHIC of the Collins asymmetries for positive and negative pion production in transversely polarized proton-proton collisions. *The Collins TMD distribution describes a spin–momentum correlation in the process of hadronization and is shown here as a function* j_T, *the momentum of the pion transverse to the jet axis. Theoretical evaluations are shown as bands that do not describe the* π^+ *data well, indicating the need for improved theoretical understanding [5].*

To understand how quarks and gluons in QCD relate to detectable bound states requires studying additional hadrons (i.e., beyond protons and neutrons). Mesons built from the lightest up, down, and strange quarks, such as the pions, kaons, and etas, are the lightest hadrons and are the most abundantly produced. Studying these mesons can provide insight into the mechanism responsible for the emergence of hadron mass and can be used to determine the ratio of the up and down quark masses in a model-independent manner. Measurements of pion structure and the pion decay rate were recently completed at Jefferson Lab, and a wider program of meson structure studies is planned at Jefferson Lab and at the EIC.

3.2.5. Spectrum of excited hadrons

Just as atomic spectroscopy explores excited states of atoms by studying decays to their ground states by photon emission, hadron spectroscopy explores the possible bound combinations of quarks and gluons allowed by the interactions of QCD. Most hadrons, beyond the lightest few, appear as short-lived reso-

Sidebar 3.2 The Pressure Inside the Proton

In the history of the universe, protons were formed microseconds after the Big Bang, when the universe expanded and cooled sufficiently for the binding forces to become strong enough to freeze quarks and gluons together into protons and neutrons, the building blocks of the atom's nucleus.

The internal structure of the proton has been studied in great detail using the electromagnetic interaction as a probe. The elastic form factors, its internal distribution of charge and magnetism, have been studied for the past 70 years. Its quark structure has been studied for over 55 years, and its helicity, or spin structure, for over 40 years. In contrast, we know very little about the proton's mechanical properties: its internal mass distribution, angular momentum, pressure and shear stress. These properties are encoded in gravitational form factors, which can be probed directly only in the proton's interaction with gravity- a practical impossibility due to the extreme weakness of the gravitational force. Thus, the mechanical properties were completely unknown until recently.

A theoretical breakthrough enabled the first experimental extraction of one of the gravitational form factors, D(t), and the determination of the pressure distribution inside the proton shown in Figure 1 obtained in 2018 by scientists

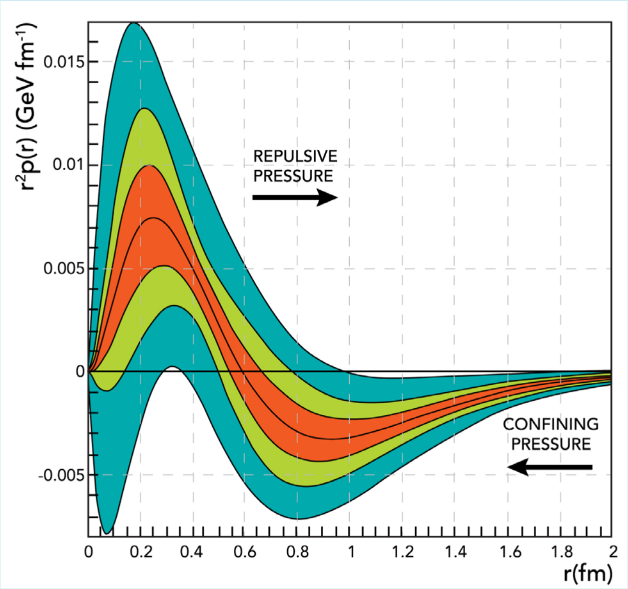


Figure 1. Pressure distribution in the proton weighted as $r^2p(r)$. *The peak pressure at r = 0 corresponds to* 10^{35} *Pascal. The green shaded bands represent uncertainties if only initial world data (dark) or more recent high statistics data (light) are included. The red band represent projections of future experiments [S10].*

nances that promptly decay into detectable lighter hadrons. Characteristic quantum properties of the hadron resonances are inferred from the measured distribution of the decay products. By grouping together hadrons with related characteristics, we build families of hadrons.

Of the hundreds of hadrons observed throughout several decades of experiments, most appear to have a valence content of either a quark and an antiquark or three quarks, including many newly observed nucleon excitations extracted by the CLAS experiment at Jefferson Lab. However, some do not, particularly many discovered in the past 20 years, the so-called XYZP states, which are candidates to be tetraquarks (made up of two quarks and two antiquarks) or pentaquarks (made up of four quarks and one antiquark). The strong coupling of gluons to quarks and to other gluons suggests that we should also see families of hadrons in which gluons play an essential role in determining their properties, known as hybrids. The presence or absence of these various exotic hadrons tests our understanding of how constituent particles can be bound within QCD.

Searches for hybrid mesons have, in the past, yielded results that defy explanation within QCD. More recently, by subjecting experimental data to an analysis built on rigorous theoretical constraints, we have resolved a puzzle in which two unexplained low-lying excited states were shown to be caused by a single rapidly decaying resonance, in agreement with the predictions of lattice QCD. This resonance has been studied in greater detail in lattice QCD (Sidebar 3.1), where it was found that the previously observed decay modes are rare decays, with the state decaying copiously into a particular set of hadrons that has not yet been examined experimentally. This example indicates how the field of hadron spectroscopy has evolved such that high-quality experimental data are analyzed using rigorous theoretical tools and first-principles calculations of the same quantities can be performed within lattice QCD.

from Jefferson Lab. These results were based on the analysis of deeply virtual Compton scattering (DVCS) data, measured with the CEBAF Large Acceptance Spectrometer CLAS, and combined with information provided by generalized parton distributions (GPDs), a theoretical framework for mapping out the internal structure of protons.

The comparison of peak pressure measured in various regions and objects on Earth, in the solar system, and in the universe are displayed in Figure 2. The tiny proton with a peak pressure of 10^{35} Pascal beats them all, including the most densely packed known macroscopic objects in the universe -the cores of neutron stars.

With current and planned state-of-the-art experimental facilities, further development and breakthroughs in theory and in lattice QCD, we will be able to reveal more of the mystery of the strong force, the most powerful force in nature, that binds quarks together to form the fundamental building blocks of the atomic nuclei.

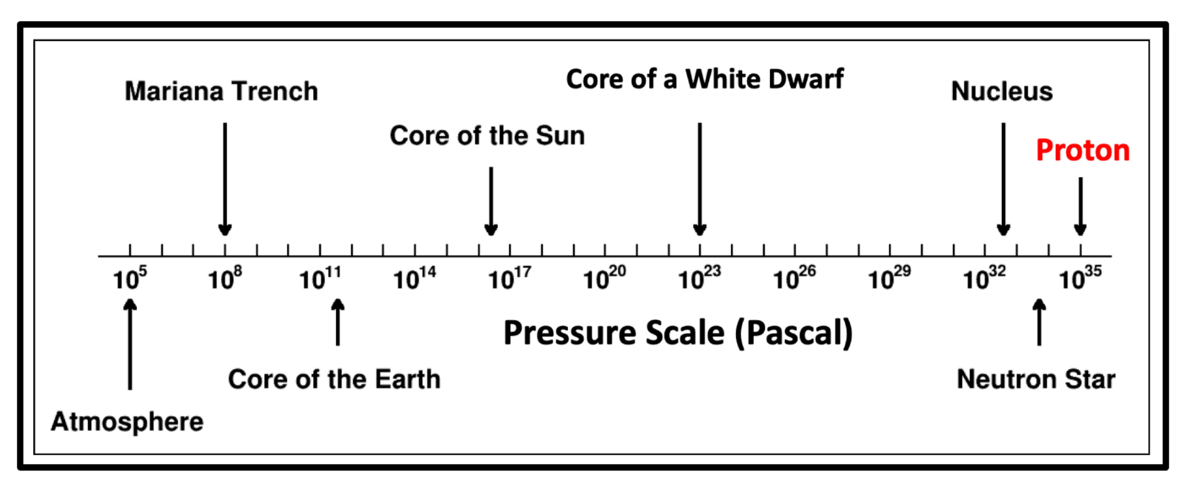


Figure 2. Peak pressure of objects in the universe, including the peak pressure inside the proton [S11].

The GlueX and CLAS12 detectors at Jefferson Lab provide powerful tools for studying the spectrum of hadrons built from light quarks and gluons. A robust experimental program with CLAS12 has focused on measurements of the transitions between the ground and excited baryon states for a range of energy and momentum transfer Q^2, which will enable us to study how hadron structure emerges from QCD. GlueX has already collected a photoproduction dataset of unprecedented size and quality, and the analy-

Sidebar 3.3 Connecting the World of QCD to the Visible World.

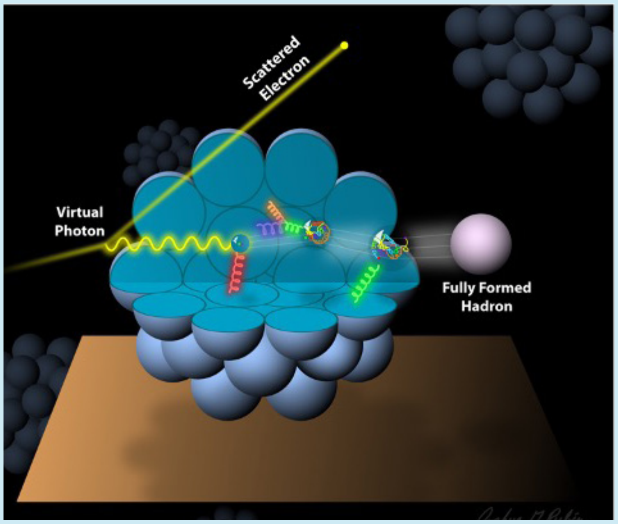


Figure 1. Representation of a high energy collision [S12].

Because of confinement, we never observe the color-charged particles of QCD—quarks and gluons—in isolation; they are confined to color-neutral hadrons. Thus, every time a high-energy collision breaks up a proton, the energy of the collision allows the creation of more quark–antiquark pairs by converting energy into mass ($E = mc^2$), and the new quarks and antiquarks rapidly bind to the various constituents of the broken-up proton, "snapping" into mesons and baryons, the QCD bound states, which can be detected.

Like blowing soap bubbles from the film with a bubble wand, when every free-streaming bubble must have closed off to become a whole bubble, every free-streaming product of a high-energy collision must have somehow become a "whole" color-neutral particle (Figure 1). Each time you blow on the soap film, a different number of bubbles of varying sizes may be produced. Likewise, each time a high-energy collision involving a proton occurs, a different number of hadrons of varying masses and quantum numbers may be produced.

To date, most efforts have focused on studying the production of a single hadron at a time along the same direction as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticated ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation measurements in hadronization by the STAR experiment at RHIC, multivariable measurements of identified hadron production in jets by the LHCb experiment at CERN, an investigation by the CLAS experiment at Jefferson Lab of how hadron-pair production is modified in cold nuclear matter, and the modifications to hadrons in jets induced by interactions with the quark–gluon plasma, observed at both RHIC and the LHC.

These exciting results naturally point to more questions.

- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization change in a dense partonic environment?

The upcoming decade holds great promise for advancements, both in how we think about hadronization theoretically and in our ability to experimentally untangle the various mechanisms that contribute to this phenomenon. Theoretically, recent developments in quantum computing provide unique opportunities to explore the inherent dynamic nature of hadronization as a process unfolding in time. Experimentally, hadron identification capabilities at the STAR experiment at RHIC, CLAS12 experiment at Jefferson Lab, LHCb and ALICE experiments at CERN, Belle II experiment in Japan, and the ePIC experiment at the future EIC will allow us to measure and compare a wide range of traditional and novel observables related to hadronization.

sis of these data is underway. Current efforts are directed at building reliable theoretical descriptions of the production processes in play. Continuing to run CEBAF at 12 GeV will allow data to be collected even for relatively rare decay modes; in parallel, analyses of increasingly complex final states will aim to map complete families of exotic hadrons.

High-energy experiments (such as at the LHC) have delivered a steady stream of surprises in the form of the XYZP states, newly observed hadrons that contain heavy charm quarks but do not fit into previously successful models. Nuclear physics facilities can help resolve mysteries generated by these new observations by investigating these states in more direct production processes, free from many of the complications present in the discovery mechanisms. At the limit of the current CEBAF beam energy, searches in Hall C and GlueX have thus far seen no signal for the observed pentaquark candidates, limiting the possible interpretations of the high-energy results. To investigate the other XYZP states, higher beam energy is required; the tetraquark candidate Z_c states would be copiously produced at a high-luminosity, fixed-target electron machine operating above 20 GeV.

3.2.6. QCD and nuclei

The picture of nuclei as collections of nucleons exchanging virtual mesons has successfully explained numerous nuclear phenomena. Advances in accelerator and detector technologies have enabled us to probe deeply into the nucleus and observe effects from the quark and gluon constituents of nucleons. Examples include the EMC effect, attributed to the modification of the partonic structure of nucleons when embedded in a nucleus, or short-range correlations (SRCs), referring to pairs of high-momentum strongly interacting nucleons inside a nucleus, whose separation distance is comparable to their radii.

SRCs have been extensively studied at Jefferson Lab since the last Long Range Plan. At intermediate relative momenta, most are neutron–proton pairs, but at high momenta the ratios of proton–proton and neutron–proton pairs are consistent with the simple counting of quantum states. The modification of quark momenta in nuclei—the EMC effect—is found to increase linearly with the number of SRC pairs, suggesting that the short-distance nucleon–nucleon interaction could modify nucleon structure. Further measurements are being carried out to study the relationship between EMC and SRC in light nuclei (to probe the connection to the detailed nuclear environment) and heavier nuclei (to understand the dependence on the numbers of protons and neutrons).

Whether the EMC effect involves any spin dependence has never been explored. The spin structure function EMC effect could provide complementary information; a first measurement of the polarized EMC ratio in lithium-7 is planned. Furthermore, by contrasting structure function measurements in calcium-40 and calcium-48, we can study the quark flavor dependence of the EMC effect. Another novel method is to measure the PVDIS asymmetry in calcium-48 with SoLID at Jefferson Lab, which effectively yields the ratio of weak to electromagnetic couplings and is thus sensitive to the ratio of quark flavors.

One of the hottest topics in astrophysics concerns the observation of neutron stars exceeding two solar masses. This observation contradicts the predicted limit of no more than 1.5 solar masses using current estimates for the hyperon–nucleon interaction. A hyperon is a baryon containing at least one strange quark. Examples include the lambda and sigma baryons, which are somewhat heavier than the proton and neutron. This discovery calls for a more detailed understanding of this interaction, and more specifically the isospin dependence of the two-body interactions between a hyperon and a proton or neutron, as well as the properties of the three-body hyperon–nucleon–nucleon force. Jefferson Lab programs have been delivering data for quantitative hyperon–nucleon interaction studies by means of hypernucleus measurements and hyperon–nucleon scattering. Future high-resolution hypernuclear experiments at Jefferson Lab in Halls A and C and efforts to isolate hyperon–nucleon scattering in Hall B provide critical measurements to help solve this interdisciplinary problem.

Nuclei have also been probed in high-energy nuclear collisions at RHIC and the LHC. These collisions provide data that are particularly sensitive to the gluonic structure inside nuclei. These data can be used to study the onset of gluon saturation. Collisions of protons with heavy nuclei and ultraperipheral heavy ion collisions have already provided hints at the existence of gluon saturation effects. In the future, the RHIC hadron physics program, with the upgraded STAR detector and the new Super PHENIX (sPHENIX) detector, as well as LHC measurements with LHC beauty (LHCb) and the forward calorimeter (FoCal) upgrade to A Large Ion Collider Experiment (ALICE), will contribute to constraining nuclear PDFs and advancing our understanding of gluon dynamics in hadronic matter.

3.3 THE PHASES OF QCD—RECREATING THE MATTER IN THE EARLY UNIVERSE

Hot QCD is the study of extremely high-temperature and high-density matter. Collisions of large nuclei at

RHIC and the LHC create a plasma of quarks and gluons with the properties of the early universe, at temperatures of trillions of degrees and with near symmetry between matter and antimatter. This hot regime of QCD lies at the intersection of nuclear physics with many-body quantum field theory, relativistic fluid dynamics, and condensed matter and has implications for applications well outside the realm of subatomic physics. The evolution of a heavy ion collision is illustrated in Figure 3.6, indicating the different stages and time scales, and showing the various final-state particles that carry all accessible information.

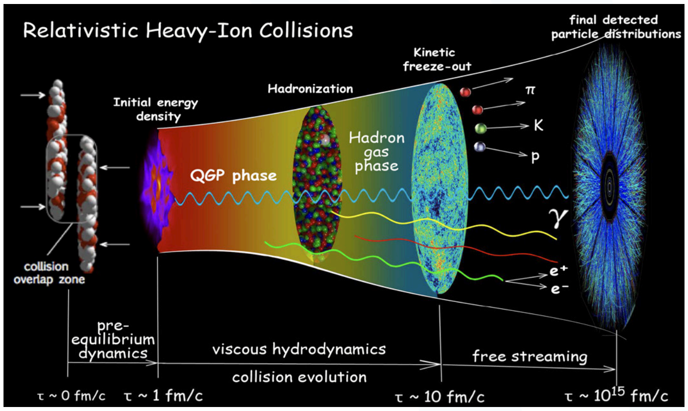


Figure 3.6. The stages of a relativistic heavy ion collision [6].

The newly built sPHENIX detector and upgraded STAR detector at RHIC, together with increased luminosity at the LHC and upgraded ALICE, A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS) and LHCb detectors, will enable a multi-messenger era for hot QCD based on the combined constraining power of low-energy hadrons, jets, electromagnetic radiation, heavy quarks, and exotic bound states. Successful theory collaborations offer breakthroughs in the next decade. State-of-the-art numerical simulations, assisted by ML techniques, will provide quantified uncertainties on the viscosities, jet transport coefficients, and other properties of this novel plasma and their dependence on temperature. The following essential questions will be addressed by hot QCD:

1. ***How do the fundamental interactions between quarks and gluons lead to the perfect fluid behavior of the quark–gluon plasma?***

   The QGP flows like a very low-viscosity fluid. However, elucidating the mechanism by which this fluid behavior emerges from the fundamental interactions between quarks and gluons requires probing QGP with high-momentum gluons, light quarks, and heavy quarks as well as measuring the structure inside the jets of particles emerging from them. These probes scan the plasma at different distance scales.

2. ***What are the limits on the fluid behavior of matter?***

   Signals of fluid behavior have been observed in large and small colliding systems, including collisions of protons with heavy ions or even with other protons. Identifying when we see this fluid and why requires improved theoretical tools and high-statistics measurements in small colliding systems.

3. ***What are the properties of QCD matter?***

   The equations that describe the static and dynamic properties of nuclear matter, including the (shear and bulk) viscosity and diffusion, are determined by constraining theoretical models with measurements of particle flow, jets, and heavy quarks and their bound states. Insights into the many-body interactions can have significance beyond QCD, in particular for warm, dense plasmas in fusion experiments and trapped cold fermions.

4. ***What is the correct phase diagram of nuclear matter?***

   We have established that the transition between hadrons and the QGP at low baryon density is a smooth crossover. We must still determine whether a first-order phase transition (comparable to that between liquid water and vapor) exists at higher baryon density and, consequently, a critical point. Heavy ion collisions over a range of energies, combined with complementary information from neutron star observations, will help us address this topic.

RHIC will complete its groundbreaking science program in the coming years, employing the new sPHENIX detector and upgraded STAR detector to address these science questions. As RHIC is transitioned into the EIC, the LHC heavy ion program will lead the world in hot QCD physics.

3.3.1. Quark–gluon plasma properties

3.3.1.1. Flow in large and small systems

The QGP, formed when quarks and gluons are released from within protons and neutrons, is a special kind of matter. The QGP behaves like a fluid; in fact, it is the most perfect fluid ever observed. Experiments to characterize plasma dynamics have become increasingly precise, placing new constraints on how the plasma transports particles, energy, and momentum. Calibrated simulations help provide a complete picture of transport in the QGP and help us understand how this plasma behaves.

Collisions of small nuclei offer a unique testing ground to study how the QGP becomes an almost perfect fluid and how viscous, or sticky, the plasma is. Understanding how small a QGP droplet can be will set limits on the fluid behavior of matter. Gold and lead nuclei are much larger than protons or even helium-3 nuclei, so the overlap region of these heavier nuclei is much larger than for proton–nucleus collisions. Surprisingly, even proton–nucleus and helium-3–nucleus collisions show characteristic correlations of collective responses, albeit less pronounced than in larger colliding systems. Thus, even in these tiny collisions, patterns of particles acting together can be seen. These responses had long been attributed to the QGP.

The ability to make and interpret these measurements is only possible because of significant technical progress since 2015, both in experiment and theory. However, improvements of the early time descriptions, known as the initial state, are still needed: for example, going beyond the popular assumption of a purely gluonic initial state. Improved precision on the determination of the QGP viscosities requires both theoretical and experimental improvements, such as increasingly larger datasets and new or upgraded detectors to facilitate precise measurements over a variety of collision systems and energies. A key challenge is to separate properties of the initial colliding nuclei from those of the QGP. Measurements of multiparticle correlations over a wide kinematic range will impose strong constraints on QGP properties by separating effects from the initial, bulk evolution, and hadronization stages.

Extended acceptance, improved event plane and triggering capabilities, and the ability to probe the previously inaccessible forward region (by detecting particles produced close to the beamline) are all exploited in RHIC's Hot QCD program. New measurements of soft, hard, and electromagnetic probes will allow STAR and sPHENIX to address important questions about the fundamental properties of the QGP, including the temperature dependence of the viscosities, the 3D nature of the initial state, how vortices can affect the particles' motion on the short timescales of the collision, and the chiral properties of the medium.

3.3.1.2. Exploring the plasma: Quantum effects and record rotation speeds

Why does the universe contain more matter than antimatter? This question is one of the biggest questions in physics because most physics processes produce both in equal quantities. One part of the solution could lie within heavy ion collisions, where the QGP is formed at a similar high temperature and density as the early universe.

Particles can have a handedness, called chirality. Right-handed particles have spins that line up with their momentum, and left-handed particles will have spins that are antialigned. If a magnetic field is applied to a system of chiral charged particles, then the spins of all the particles will line up with the magnetic field and left-handed and right-handed particles would move in opposite directions, which is called the chiral magnetic effect (CME).

This novel effect was predicted to be possible in the QGP formed in heavy ion collisions, where we would observe an electric charge separation along the large magnetic fields created by the moving charged colliding nuclei in grazing collisions of heavy ions. The presence of the CME in a QGP would provide evidence of chiral symmetry restoration, a fundamental feature of QCD at high temperatures. The most controlled CME search was performed by the STAR collaboration at RHIC using ruthenium–ruthenium and zirconium–zirconium collisions. These elements have the same number of nucleons but a different number of protons and neutrons and thus should create different strength magnetic fields during the collision while keeping most other properties of the collision the same. Rigorous blind analyses showed no evidence of the CME in heavy ion collisions.

When the colliding nuclei do not hit each other head on, the resulting QGP droplet will be spinning extremely rapidly. This resulting **vorticity** is transferred to the hadrons' **spin polarization**, which was first observed in the polarization of lambda baryons in gold–gold collisions at center-of-mass energies between 7.7 and 39 GeV. The lambda baryons are unique in that the direction of their spin can be determined based on the angles of their decay products. This relationship indicates that the QGP is spinning faster than any fluid ever observed: its angular rotations are approximately 10^{21} Hz. Viscous **hydrodynamic** calculations were able to reproduce the observations without any special tuning. This achievement alone is a nontrivial confirmation of the validity of the hydrodynamic, local-equilibrium paradigm underlying our understanding of the bulk system created in heavy ion collisions. However, the relationship between vorticcity and collective flow is not yet understood; additional shear terms will be needed to capture the entirety of the QGP fluid behavior.

3.3.1.3. Imaging the plasma using jets

The QGP droplets formed in the collision of nuclei exist for such a short time that it is impossible to use an external source to probe the medium and understand its properties. Fortunately, QCD has given us a useful internal probe in the form of particle jets. These jets are formed in the collisions when high-momentum transfer scatterings of quarks or gluons occur, producing the showers of particles known as jets. Jets are modified by interactions of the scattered quark or gluon with the medium, causing the jet to radiate additional gluons, decreasing the energy of the final jet. During the last two decades, major progress in understanding this so-called quenching of jets has been driven by increasingly precise and differential measurements from the LHC and RHIC thanks to their increased luminosity and upgraded detectors, as well as improvements in theory.

Since the last Long Range Plan, significant advances have been made in quantifying jet quenching and jet substructure in the QGP, using data to constrain hydrodynamic models combined with state-of-the-art calculations of the interactions of quarks and gluon inside the plasma. These advances indicate how energy is transported inside the plasma. Open-source software modeling environments such as JETSCAPE can now provide a systematic analysis of the different theoretical approaches and different observables.

Jets in heavy ion collisions have modified internal structure compared with proton–proton collisions, and we still do not know how far a jet can travel through QGP while the particles inside it remain correlated. Measurements of jet substructure, described in Sidebar 3.4, have advanced dramatically, giving some first answers about how jet quenching and the jet shower structure are related. Measuring the fate of jets with different initial properties will allow us to study the internal structure of the QGP.

The QGP is itself modified by the passage of a jet: an increased yield of low momentum particles occurs within and around the jet. The plasma response to perturbations from jets is closely connected to how the QGP achieves equilibrium early in the collision. Determining whether a jet started from a gluon, a light quark, or a heavy quark is also important to fully characterize the QGP and its effects on the jet shower; gluon jets are expected to lose more energy than quark jets. Unambiguously determining the jet origin is complicated. Quark-initiated jets can be selected via jets balanced by a photon or a Z boson, which is

Sidebar 3.4 Quark Gluon Plasma and the Interior of Jets

Particle jets are an essential probe of the properties of the quark–gluon plasma (QGP). The evolution of a jet includes three stages, illustrated in Figure 1. In the first stage, a shower of gluons and quarks (partons) is emitted from an energetic quark or gluon produced in a collision. Next, the plasma medium induces extra gluon radiation from the jet constituents. These gluons interact with the QGP, causing a cascade that transfers energy from the initial quark or gluon into the plasma. In the last stage, gluons are radiated outside the plasma until the final-state hadrons emerge. These hadrons are collected in a jet. During the cascade, quantum interference (i.e., coherence) can suppress radiation of gluons with large wavelength (i.e., low energy).

The substructure, or interior, of jets in elementary particle collisions is well described by QCD. However, the processes by which quarks and gluons lose energy in QGP can rearrange particles inside jets and modify their energies. Furthermore, jets can also affect particles within the plasma, just as a boat creates a wake as it moves through water (Figure 1).

A suite of measurements has provided information about the substructure of these jets. The measurements shed light on the radiated gluons, interactions in QGP, and how well the entire process can be described by QCD. The energy profile as a function of the distance from the jet axis and the momentum carried by individual particles within a jet were studied at both RHIC and the LHC. The results showed that some of the original jet's energy is redistributed in the QGP and is carried away predominantly by low-energy particles. Although some of these results are reproduced by QCD calculations, the low-energy particles are not yet understood. Precise data are needed to inform models of the energy redistribution and whether quarks and gluons are affected differently.

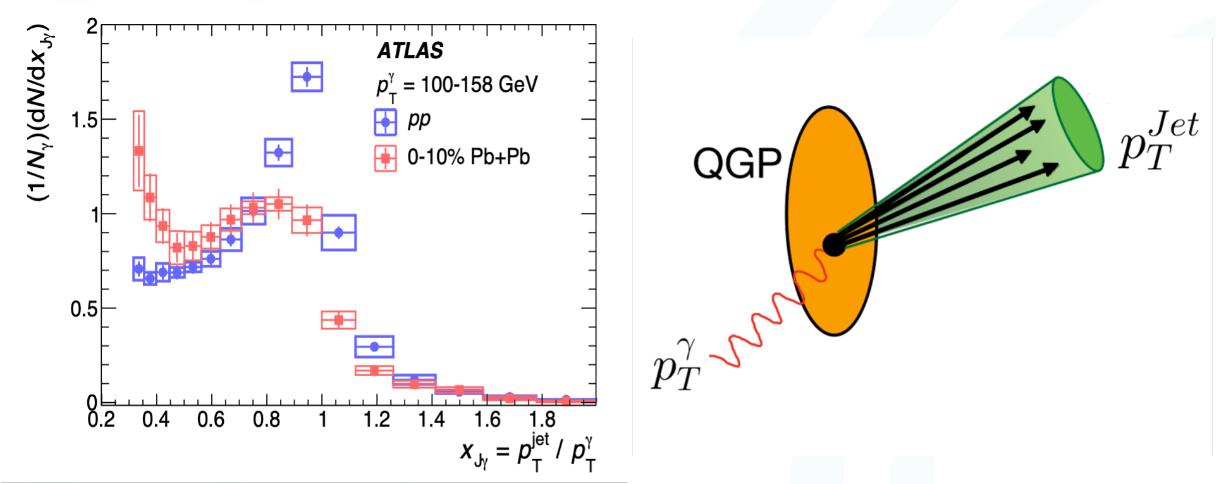


Figure 3.7. Using jets to image the QGP *(left) The ratio of a jet's momentum to that of its high-energy photon partner from proton–proton collisions (blue) and lead–lead collisions (red). Jet quenching causes the distribution to shift to a lower ratio and can be quantified using the photon's energy, which should be very closely related to the initial energy of the quark that initiated the jet. (right) A diagram of a photon jet measurement [7].*

essentially a very heavy photon, as shown in Figure 3.7. Jets that include the much heavier charm or bottom quarks have different medium-induced radiation and can allow, for example, diffusion properties to be determined. The emission of gluons from a heavy quark is different than from light quarks or gluons because heavy quark mass affects both the scattering and radiation processes.

3.3.1.4. Insights from heavy quark and electromagnetic probes

The study of heavy quarks in heavy ion collisions has provided new insights into the properties of the

Jet substructure observables defined using the momentum and angle of each jet particle can follow sequential gluon emission and can be both measured and predicted by theory. For example, characteristic scales of jet–medium interactions are encoded in jet angularity, jet mass (or total energy), and jet splitting functions. Data show a narrowing of the jet core along with additional low-momentum particles at the jet's outer edge. More precise data and improved theoretical tools are needed to determine the scale of coherence among jet particles.

The new sPHENIX detector, STAR upgrades, and upgraded LHC experiments will elucidate the multiscale, spacetime evolution of jets and the QGP. Jets and their substructure will also probe QCD in nucleons and nuclei at the EIC.

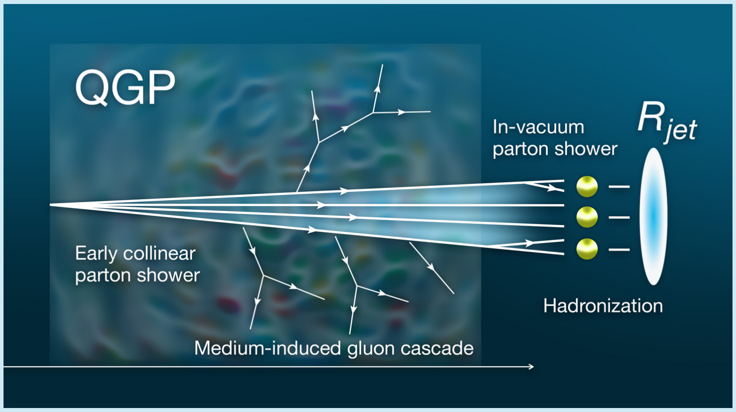


Figure 1. Schematic of jet evolution and interaction with quark–gluon plasma [S13].

medium and how it affects heavy quarks and their bound states. Two types of heavy quarks—charm and bottom quarks—are valuable because their mass is significantly larger than the temperature of the system, so they can be used to probe the QGP at short distances. Measurements at RHIC and the LHC include different decay channels for mesons that have charm and bottom quarks and confirm that energy loss in the QGP decreases with increasing quark mass.

Measurements of charm mesons and baryons, reconstructed from the light hadrons into which they decay, elucidate the mechanism by which quarks and gluons form the hadrons observed in detectors, as shown in Figure 3.8. Recent data show that heavy quarks coalesce with co-moving quarks and gluons, some of which may come from the QGP. A thermal model of charmed meson production works remarkably well. At the time of the last Long Range Plan, little was known about charm quark diffusion in the QGP. Now, a combination of precision data and improved theories has helped us describe how the charm quarks move through the QGP.

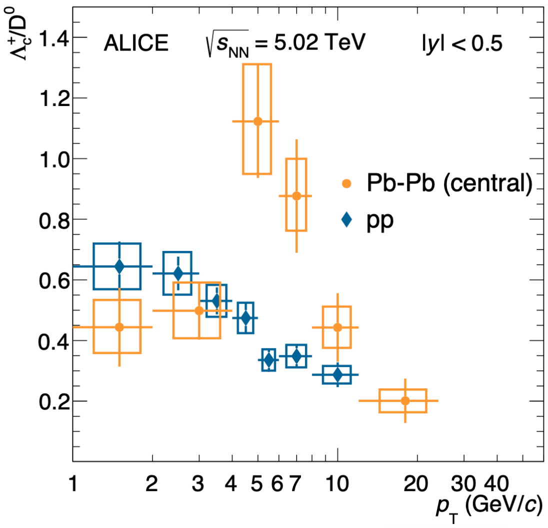


Figure 3.8. The ratio of the charm baryon Λ^+_c to the charm meson D^0 in lead–lead collisions as a function of transverse momentum. *The orange points show the ratio for the most head-on collisions and the blue points for proton–proton collisions in which no QGP should be formed at all. The significant enhancement of the ratio observed in lead–lead collisions compared with the proton–proton case indicates that charm baryons and mesons are formed via the coalescence of heavy quarks with co-moving quarks and gluons [8].*

Bound states of heavy quark–antiquark pairs should dissociate because of screening in the QGP. Lattice QCD calculations, enabled by increased computing power, show that the lifetime of such pairs decreases as temperature increases or their binding energy decreases. This causes the sequential melting of bottomonium states, which consist of a bottom and antibottom quark pair, as observed at the LHC. However, lattice QCD shows that charm hadrons can still exist above the phase-transition temperature. More precise data are needed to understand these states. The sPHENIX detector is optimized to separate the three bottomonium states. Measurements with sPHENIX and at the upgraded LHC will provide much stronger constraints on suppression of the three bottomonium states, probing the temperature dependence of quark correlations in the plasma, as shown in Figure 3.9.

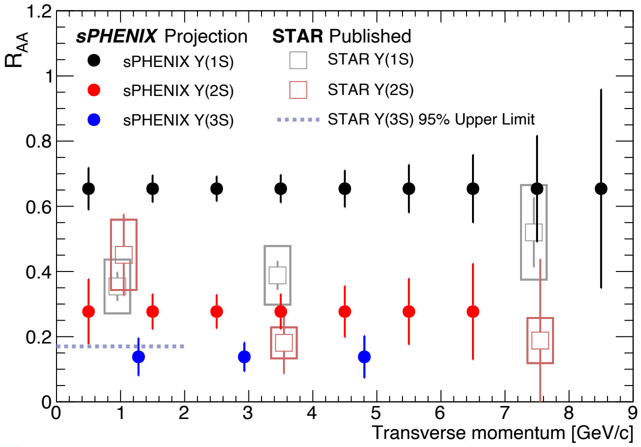


Figure 3.9. The transverse momentum dependence of the nuclear modification factor, R_{AA}. *Shown are the three lowest-mass Upsilon states that will be measured by sPHENIX (solid circles) compared with published STAR measurements for the two lowest-mass states (open rectangles) [9].*

Once produced in the collision, photons and dileptons (lepton and antilepton pairs) do not interact further, providing access to the plasma's entire history. High-energy photons, dileptons, and weak bosons are mainly produced when the nuclei first collide, reflecting initial properties of the collisions. However, low-energy direct photon spectra are enhanced relative to scaled proton-proton spectra, suggesting thermal radiation from the hot QGP. Properties of these photons, however, are not yet understood. At RHIC, dileptons have been measured at various collision energies. An excess of dilepton production in the low-dilepton mass region has been observed compared with hadronic decay contributions. The excess is consistent with in-medium broadening of the mass distribution of a vector meson (ρ-meson), which decays into dileptons. Thermal emissions of photons and dileptons have also been calculated. Electromagnetic emission channels have now been included in the modeling of the last stage of heavy ion collisions. New calculations using supercomputers have also been performed in lattice QCD for dilepton production. Results using anisotropic hydrodynamics and electromagnetic emission rates from a QGP further contribute to our understanding.

ALICE in Run 3 (2022–2025) and Run 4 (2029–2032), the future experiments NA60+, Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR), and ALICE 3 with its new detector capabilities, will provide high-precision measurements of photon and dilepton production that can be used to study the phase diagram of QCD, the plasma temperature and its time evolution, medium properties such as shear and bulk viscosity and preequilibrium dynamics, as well as chiral symmetry restoration.

3.3.1.5. Mapping the QCD phase diagram

Nuclear matter in heavy ion collisions and neutron stars can be in different states or phases, depending on the temperature and other conditions such as the ratio of baryons to antibaryons. The location of the transition from a gas of hadrons to QGP and the exact nature of this transition is of fundamental interest, illustrated by the QCD phase diagram shown in Figure 3.10.

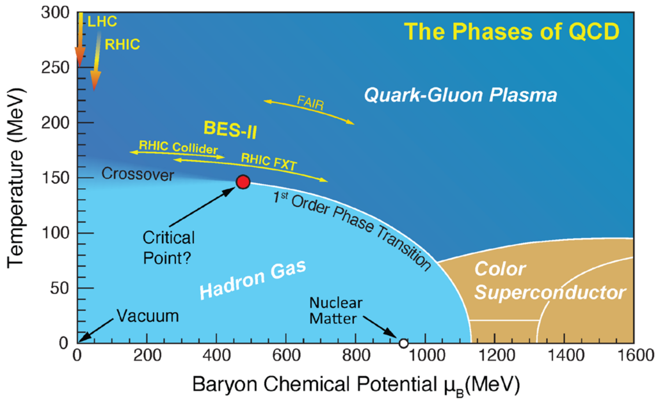


__Figure 3.10. Sketch of the QCD phase diagram, incorporating a conjectured critical endpoint and first-order transition regime.__ The coverage of the LHC, RHIC–Beam Energy Scan including the fixed target program, and the future CBM Experiment at FAIR, are indicated [10].

Changing the collision energy changes both the initial temperature of the produced matter (which contains equal amounts of matter and antimatter) and how much the protons and neutrons in the colliding nuclei (pure matter) are stopped, which leads to a larger baryon excess in the fireball at lower collision energies. Lattice QCD predicts a smooth crossover at temperature T_c = 156 ± 1.5 MeV, when baryon and antibaryon densities are equal. Models indicate a first-order phase transition at large baryon density (μ_B). If there is a crossover and a first order transition line, then they will be joined at the QCD critical point. State-of-the-art lattice calculations show a crossover up to $\mu_B/T \leq 2$. Precise calculations in the higher μ_B region are difficult, and experimental measurements are essential to determine whether a QCD critical point exists. To search for the QCD critical point and study the nuclear matter equation of state, RHIC collided heavy nuclei from 7.7 to 200 GeV in the center of mass (Beam Energy Scan I; energies are per nucleon pair). This process was followed by collisions at 7.7 to 19.6 GeV and fixed target running at 3 to 13.1 GeV (BES-II). RHIC added electron cooling to reach sufficient luminosity, and the STAR particle identification capabilities and kinematic coverage were upgraded.

Evidence for the dominance of either the QGP phase or the hadronic phase at different collision energies has been found in key observations, including critical fluctuations. At top RHIC energy, high moments of net-protons (a proxy for net-baryons) are consistent with lattice QCD predictions of a smooth crossover transition. Hydrodynamic calculations indicate that gold–gold collisions are above any critical point at center-of-mass energies above 20 GeV per nucleon pair. By contrast, at 3 GeV, hadronic interactions are evident from the measurements of moments of proton distributions, collective flow, and production of hadrons that contain strange quarks. This implies that the QCD critical point, if it exists, should be accessible in collisions with center-of-mass energies between 3 and 20 GeV. Future experiments, such as CBM at FAIR in Germany will provide additional high statistics and high-resolution data for low-energy collisions and high μ_B.

Nuclear astrophysics (Chapter 5) can benefit from insights into the equation of state gained from heavy ion collisions, even though heavy ion collisions produce nearly symmetric nuclear matter, whereas neutron stars are extremely neutron-rich environments with very few charged hadrons. Furthermore, developments in viscous relativistic hydrodynamics, triggered by the needs of the heavy ion community, can improve the description of neutron star mergers.

3.3.1.6. Initial state

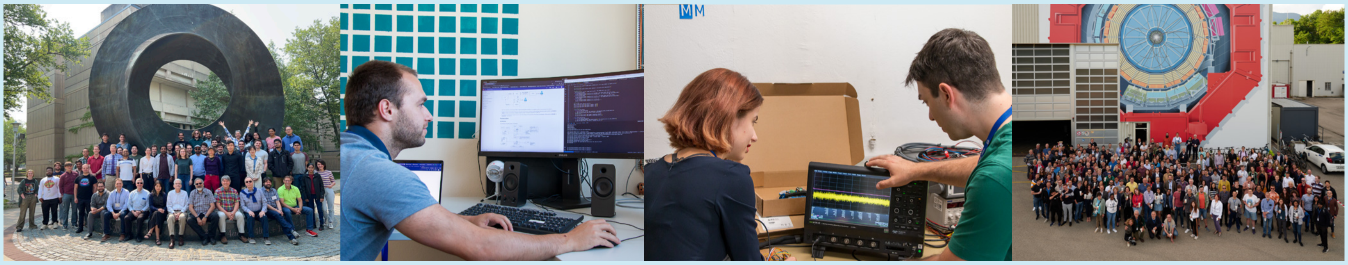
To understand the fluid behavior and the transport coefficients of the quark–gluon matter, it is important to understand the initial configuration of the colliding nuclei. Hydrodynamics and transport models depend strongly on the initial conditions. In high-energy collisions, these initial conditions are dominated by the spatial gluon distributions inside the colliding nuclei. During the last decade, it has become clear that both the average density distribution and fluctuations in the positions of nucleons and the quarks and gluons within them are important. Multiple correlation observables are measured in collisions of nuclei with different shapes and structure fluctuations. Ultraperipheral collisions, in which the electromagnetic field around one nucleus interacts with the other nucleus, provide unique ways to access quark and gluon distributions inside nuclei.

Constraining the spatial structure of quarks and gluons in nuclei is important for a description of the initial state of heavy ion collisions. Initial state models require sophisticated theory input. Frameworks that can simultaneously describe the physics of hadronic, heavy ion, and electron–ion collisions, including a description of the possible saturation of gluon number, are the ultimate goal for a standard model of QCD matter. The parameters of initial state models can be constrained using input from experimental heavy ion data. This process can and should be done in parallel with the determination of model parameters that describe QGP properties. Future theoretical work requires the full 3D structure of the initial state, the initial conditions for all conserved charges, and an improved description of the transition to hydrodynamics at early times. The EIC will enable complementary measurements of similar processes with higher precision and more controlled kinematics.

3.3.1.7. Future of hot QCD facilities

To successfully conclude the RHIC science mission, it is essential to (1) complete the sPHENIX science program as highlighted in the 2015 Long Range

Sidebar 3.5 Quantum Chromodynamics Is a Global Enterprise



Tackling the great challenges of the physics of strong interactions requires the participation of the international scientific community.

QCD research has been organized in terms of research groups, collaborations, and topical groups. The community has been supported by research centers, associations, and networks and has been boosted by international initiatives. For example, the RIKEN BNL Research Center has promoted science and technology cooperation between the United States and Japan for more than 25 years.

Research centers such as the Institute of Nuclear Theory, the Center for Frontiers in Nuclear Science and the EIC 2 Center have organized workshops and summer schools, bringing together the international communities. The Inter-American Network of Networks of QCD Challenges (I.ANN QCD), supported by NSF, in collaboration with networks and centers supported by institutions and DOE, accelerates scientific discoveries and educational training across the Americas. At present, 12 networks and 8 research centers are part of I.ANN QCD.

Photos [S14-18]

Plan, (2) complete the concurrent STAR data collection with the forward upgrade, and (3) analyze the data from all RHIC experiments. Crucially, sPHENIX, with its large acceptance, is beginning its physics program. The sPHENIX detector combination of electromagnetic calorimetry, hadronic calorimetry, precision tracking, and very high data rate will enable measurements of jets, jet substructure, and jet correlations at RHIC with a kinematic reach that is complementary to similar measurements at the LHC. The sPHENIX detector will have the first mid-rapidity hadronic calorimeter at RHIC, allowing both calorimetric and particle track-based measurements of jets and their structure.

The STAR jet physics program is improved by the combination of the detector upgrades for Beam Energy Scan phase II and the forward upgrades. Together, they extend STAR's unique particle identification capabilities to forward rapidity and down to very low transverse momentum.

At the LHC, the United States has contributed substantially to all the heavy ion experiments. With the completion of the RHIC program, we anticipate even greater participation in future experiments with the upgraded LHC luminosity. LHC experiments will enable measurements related to the properties of the QGP and the study of gluon saturation physics that is complementary to, and will enhance, experiments that will take place at the EIC. Exciting opportunities include the following:

- ALICE has implemented upgrades that enable a 100-fold increase in the data acquisition rate along with improved particle tracking performance. These upgrades, with US participation, will enable high-precision measurements of particle flow, heavy quarks, and jets. Additional tracking upgrades are planned for later in the decade that will improve the resolution by another factor of three, and the FoCal upgrade will enable photon and jet measurements in a new kinematic regime.
- With upgrades of the ATLAS and CMS experiments, long-range particle correlations and the collective behavior of the QGP will be explored down to very small angles between the produced particles and the beam direction. Moreover, the wide acceptance time-of-flight (TOF) detector upgrade planned for CMS will provide unique opportunities to study the QGP with identified hadron production and correlations.
- LHCb upgrades will allow new measurements of identified particle and heavy quark flow in a unique kinematic range. In addition to improvements to collective measurements, the CMS and ATLAS upgrades will significantly improve their already impressive jet measurement capabilities by extending their kinematic reach and particle identification capabilities.

3.3.2. Theoretical challenges

QCD is extraordinarily hard to solve in general, but powerful approximations allow us to address specific physics questions. Perturbative methods subdivide interactions into their building blocks and focus on the most important ones. They rely on the presence of a small parameter, typically the coupling strength, to organize the calculations. Depending on the energy scales, no small parameter might be available, and then nonperturbative methods, including lattice QCD and effective theories, can be invoked.

Lattice QCD, which discretizes spacetime and solves QCD on supercomputers, has determined thermodynamic properties of QCD. For time-dependent systems, and in the high baryon density region of the phase diagram, no direct lattice calculations are possible and new techniques need to be developed. Effective theories approximate QCD and are only applicable under certain conditions—yet they are powerful tools to provide insight into systems at high baryon density and explore exciting phenomena such as the QCD critical point, chiral symmetry breaking, color superconductivity, and the equilibration of relativistic media.

Hydrodynamics, a powerful effective theory of QCD, has made the discovery of the near perfect fluid behavior of the QGP possible. To make progress, we need more accurate initial-state models and more widely utilized hydrodynamic simulations in three spatial dimensions, which are necessary for modeling collisions of light nuclei and heavy ion collisions at energies lower than top RHIC energy. Many phenomena rely on the experimental observation of characteristic fluctuations, which must be incorporated into simulations. Such advances require at least two orders of magnitude more computational resources than those currently in use. With decreasing collision energy, hadronic transport simulations increase in importance. They allow us to extract the equation of state at high baryon density and constrain its isospin dependence. Precision calculations will require reassessing in-medium nucleon–nucleon interactions.

Heavy quarks, jets, and other high-momentum probes help elucidate the microscopic behavior of the QGP and allow us to explore fascinating features of QCD emerging from the presence of different color charges and the self-interactions of gluons; these phenomena distinguish QCD from quantum electrodynamics.

Transport properties of heavy quarks in a hot QCD medium have been determined using lattice QCD (Sidebar 3.1). Future challenges include extrapolation from discretized lattices to the continuous space we live in with realistic parameters, requiring exascale computing resources. Larger lattices will help clarify a broad range of heavy quark and bound state properties in the medium, which need to be supplemented by dynamical in-medium simulations and sophisticated hadronization prescriptions.

Progress is also needed in the theoretical understanding of high momentum partons in the medium. More accurately describing in-medium parton showers requires higher order perturbative QCD calculations. These will describe the internal structure of jets and teach us about the detailed microscopic interactions of QCD. Future progress will also rely on high performance computational tools, such as Monte Carlo event generators and lattice techniques. Theoretical collaborations, in partnership with experimental consortia and new computational tools, have been assembled to address these challenges (Sidebars 3.5, 3.6, 3.7).

3.4 THE ELECTRON–ION COLLIDER: A POWERFUL NEW MICROSCOPE TO LAUNCH A NEW ERA OF DISCOVERY

The EIC will be a powerful discovery machine, a precision “microscope” capable of taking 3D pictures of nuclear matter at femtometer scales. It will open a new frontier in nuclear physics, one which the scientific community has been building the foundation for over the past two decades. The EIC initiative was driven by maintaining US leadership in both nuclear science and accelerator physics and technology. These dual goals were clear from the outset, starting with the 2002 NSAC Long Range Plan where “R&D over the next three years to address EIC design issues” was a high priority. Support from the community continued with the 2007 Long Range Plan, which recommended “the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron–Ion Collider” and culminated in the 2015 plan, where the EIC

Sidebar 3.6 Quantum Simulation for Nuclear Physics

As Richard Feynman and others explained in the early 1980s, future quantum computers are expected to enable simulations of physically important quantum systems that are beyond the capabilities of classical high-performance computing (HPC). By considering the projected HPC requirements to classically simulate important quantities for nuclear physics, scientists have identified longer-term quantum simulation objectives. Quantum computation of the future is expected to efficiently simulate the structure and dynamics of dense matter systems, providing results that are not possible with classical computing technology, and which are essential to support and guide nuclear experiment and theory. Cancellations among numerical contributions that are fundamentally quantum-mechanical in origin require classical computing resources to scale exponentially with system size, severely limiting their impact. Examples of the physical systems that require quantum computing include complex nuclear reactions and structure, the evolution of nonequilibrium quark–gluon matter produced in high-energy collisions, and neutrino flavor oscillations in supernovae. To elaborate on one of these, in the case of high-energy collisions of nuclei, quarks and gluons can be produced in the collision that move through a liquid of lower-energy quarks and gluons. In so doing, they exchange color, energy and momentum to eventually form colorless jets of hadrons that enter detectors through color screening processes. Quantum computers of the future are expected to robustly simulate this complex process.

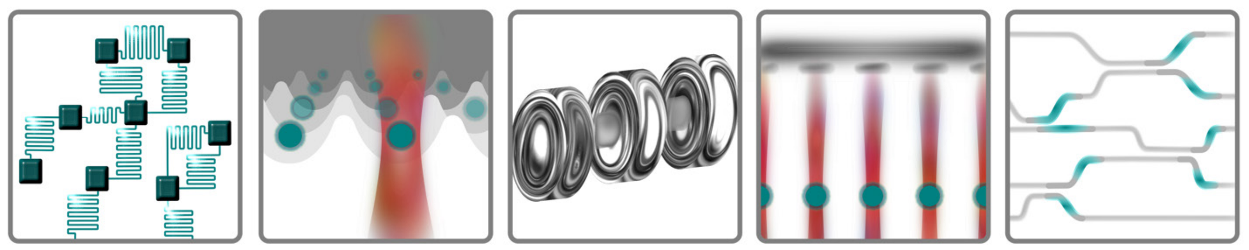


Figure 1: An increasingly diverse array of quantum hardware is being used for quantum simulations of nuclear physics observables based upon, for example (from left to right) superconducting qubits, cold-atom and Rydberg arrays, superconducting radio-frequency cavities, trapped ions, and photonics [S19].

was identified as the "highest priority for new facility construction following the completion of FRIB."

During this period, the growing EIC community continually developed and documented the science case underpinning these recommendations. A series of workshops hosted by the INT at the University of Washington laid the foundation for a white paper titled, "Understanding the glue that binds us all." The studies developed for the INT EIC white paper, combined with continued progress in accelerator R&D, served as input to a critical review in 2018 by NAS. Its final report, *An Assessment of the U.S.-Based Electron-Ion Collider Science*, concluded that "the EIC science is compelling, fundamental, and timely."

Just as new space telescopes reveal previously hidden and awe-inspiring views of the universe that revolutionize our picture and knowledge of the cosmos, the EIC promises to reveal the concealed behavior of some of the smallest known particles and transform our understanding of nuclear matter. By focusing on a new regime that has never been seen, the EIC will yield new phenomena for decades to come.

The EIC project has made tremendous progress since the previous Long Range Plan, reflecting a unified and engaged community of nuclear theorists, experimentalists, and accelerator physicists who are eager to realize the promise of a future scientific facility that can shed light on the existence of nearly all visible matter in the universe (Sidebar 3.8). The current collider design, interaction regions, and the ePIC detector, as well as the case for building a second complementary detector, are discussed in Chapter 9, "Facilities." The following sections highlight the flagship components of the EIC science case.

3.4.1. The rich science program of the Electron–Ion Collider

The EIC will be an amazingly versatile machine that will expand our knowledge of the most fundamental particles of nature and revolutionize our understanding of the structure of the protons, neutrons, and nuclei that make up the world around us. It will test our

Collaborations among universities, national laboratories and technology companies are simulating simplified theories to advance quantum algorithms, workflows and hands-on expertise, which are necessary to simulate increasingly realistic theories. They are being performed with accessible classical HPC emulators, and quantum computers and simulators that are based upon superconducting qubits, trapped ions, optical systems, cold-atom arrays, qudits, and more (Figure 1). They are paving the way toward quantum advantages in strategically identified areas, including those discussed above, which we expect to achieve within the coming decade. Our activities, from sensors to simulation, are part of the growing US quantum information science and technology (QIST) efforts, including DOE National Quantum Initiative Centers and NSF Quantum Leap Challenge Institutes.

The unique interactions that define nuclear physics, and the complexity of the emergent strongly-interacting and correlated quantum many-body systems, demand that future quantum simulation platforms have specific attributes. Co-design for these physical systems has already led to the inclusion of new operations in trapped-ion and SRF-cavity quantum devices, that can also be used for other scientific applications. Further, new techniques for classical simulations have emerged from developing quantum algorithms to solve nuclear physics problems, rendering previously intractable problems tractable. These mutually-beneficial advances at the interface of nuclear physics and QIST, in quantum simulation, quantum sensing, entanglement studies in many-body systems will continue to grow. A more complete discussion about the importance of quantum information science and technology for nuclear physics can be found in Section 10.5.1.

understanding of the Standard Model of physics by providing detailed experiments that map the spatial, momentum, and spin distributions of sea quarks and gluons, study how the gluon density evolves with the resolution of the electron probe, and observe how transitions from quarks and gluons to hadrons are modified in increasingly dense nuclear matter. The results provided by EIC experiments will help reveal the secrets of the structure and behavior of the fundamental particles of matter and thus will help elucidate the forces that shape the universe. EIC experiments will follow these key lines of inquiry:

- How do the properties of the proton such as mass and spin emerge from the sea of quarks, gluons, and their underlying interactions?
- Where are the low-momentum quarks and gluons located within the nucleon, and what do their confined motions look like?
- What happens to the gluon density in nucleons and nuclei at small *x*? Does it saturate at high energy, giving rise to gluonic matter with universal properties in all nuclei (and perhaps even in nucleons)?
- How do jets and color-charged quarks and gluons interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do quark–gluon interactions act as glue and create nuclear binding?
- Do signals from physics beyond the Standard Model manifest in electron–proton/ion collisions? If so, what can we learn about the nature of these new particles and forces?

Sidebar 3.7 Unveiling Complexity: Comprehensive Extraction of Physics through Multifold Observables

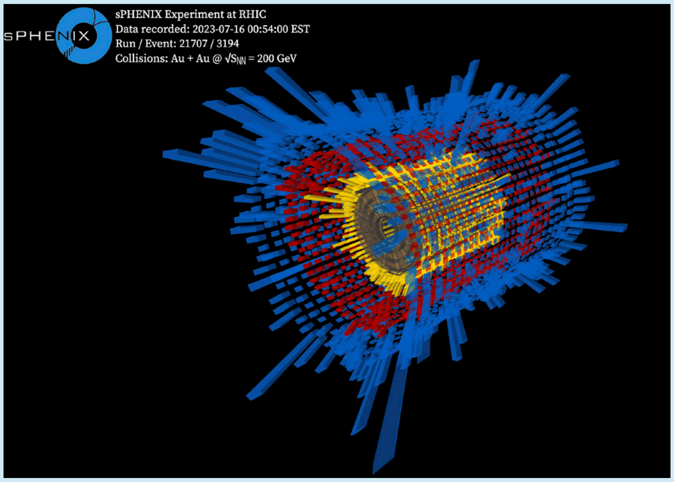


Figure 1. An sPHENIX event display [S20].

Harnessing information from many different observables

Modern heavy ion experiments can extract many different observables from the complex final-state particles emerging from a collision (Figure 1). These observables include jets, electroweak probes, low-momentum hadrons, and particles containing heavy quarks. Each observable provides unique information about different aspects of the collision. By combining information from all of them, we can gain a complete picture of the collision and extract the desired physics.

Phenomenology: Modular frameworks

Computations in heavy ion collisions require complex frameworks with many components, including an understanding of the initial state, bulk evolution, and hadronization. High-momentum, heavy quark, and electroweak probes require additional components such as the description of the initial scattering and an implementation of energy loss in the medium. Frameworks that allow interchangeable modules based on different physics assumptions are highly desirable for computing these many observables.

Theory and interdisciplinary collaborations

Theory and interdisciplinary collaborations connect scientists who have different expertise, aiding the development of such frameworks. For example, the NSF-funded JETSCAPE Collaboration—an interdisciplinary team of theorists, experimentalists, computer scientists, and statisticians—has created a framework for jet quenching calculations that includes modules for the bulk medium evolution and different energy loss and jet shower models. Its flexibility allows calculation of a large variety of observables in many different collision systems and enables the extraction of quark–gluon plasma properties. The DOE-funded BEST Collaboration has developed modules for end-to-end calculations of observables that are sensitive to critical phenomena in the RHIC Beam Energy Scan. Further collaborative theory work is needed to understand the evolution of heavy ion collisions and the underlying processes in QCD, The following subsections discuss the revolutionary impacts that the EIC will bring to these fundamental questions.

3.4.1.1. The proton spin puzzle

Fundamental particles are defined by their intrinsic properties, such as mass, charge, and spin. The term spin refers not to the rotation of a particle about its axis, but rather an inherent quantum mechanical property that manifests as a type of angular momentum. The proton is not a fundamental particle but is made up of three valence quarks and a sea of gluons and quark–antiquark pairs. Conservation laws require that the intrinsic spin and angular momentum of all these partons always sum to exactly the known inherent spin of the proton. Although the value of the proton spin is the same for all protons and has been known for more than a century, nearly half the spin of the proton is still unaccounted for. Decades of experiments have provided input into sophisticated theoretical frameworks that show that the spin of the quarks (and antiquarks) account for one-third of the proton spin, while the highest-momentum gluons contribute only 20%. The puzzle, then, is where does the rest of the spin come from?

The uncertainty in the low-x gluon contributions is demonstrated clearly in Figure 3.11, where the red line shows the most likely gluon spin distribution as a function of momentum fraction x. The light blue shaded area indicates the associated uncertainty of that determination from the existing measurements. It expands rapidly to fill the entire range of the plot for $x < 0.01$, reflecting the dearth of experimental data in this regime. The dark blue curves show the immense reduction in the uncertainty in the gluon contribution to the spin of the proton from future EIC data. The EIC will allow us to see and understand—for the first

utilizing the anticipated new data from RHIC and the LHC. Current topical collaborations apply similar methods to gain insight into the physics of heavy quarks (HEFTY Collaboration) and gluon saturation (SURGE Collaboration).

Extracting physics

By performing Bayesian inference analyses (Figure 2), JETSCAPE has completed first studies on extracting bulk medium properties and jet quenching parameters, which both quantify energy and particle transport in quark–gluon plasma. The same philosophy can be applied to future EIC experiments in which many different observables can be measured and calculated using a variety of theory components.

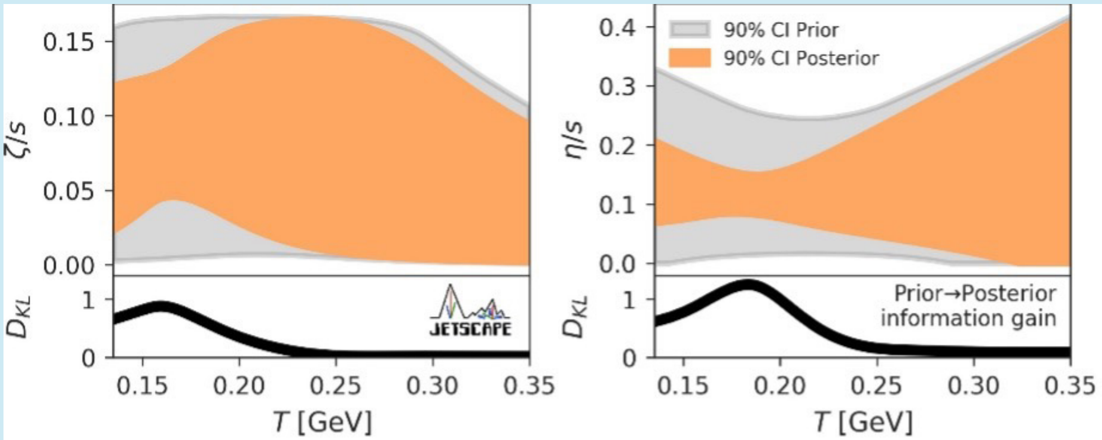


Figure 2. Temperature-dependent QCD transport coefficients, bulk viscosity (left) and shear viscosity (right) extracted from heavy ion data using a Bayesian analysis within the JETSCAPE framework. Gray bands show unconstrained input, orange bands are constrained by data. The information gain D_{KL} is shown in the bottom panels [S21].

time—this aspect of the proton's internal structure. No existing or planned future facility, other than the EIC, can answer the question of how much of the proton spin arises from the sea of low-momentum gluons.

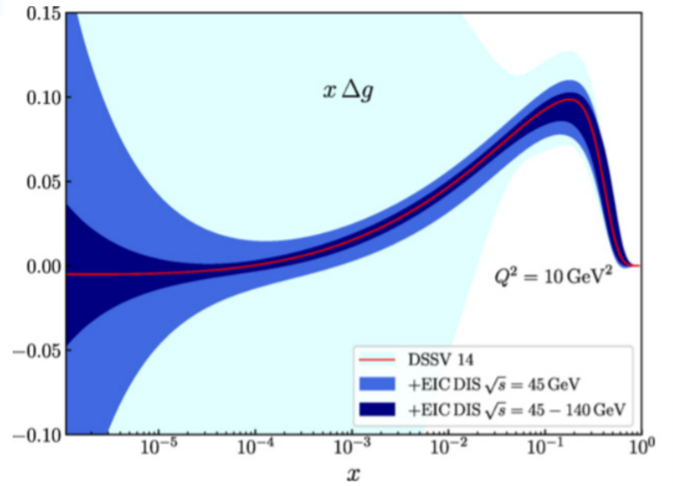


Figure 3.11. The best fit value of the gluon spin distribution from a global analysis.*The light blue band captures the uncertainty from the fit to existing data and the darker blue band shows the significant reduction that will be achieved with the EIC data [11].*

3.4.1.2. Nucleon imaging and the origin of mass

A single valence quark is hundreds of times lighter in mass than the proton. How then can three valence quarks, bound together by massless gluons, produce the known mass of the proton? The answer lies in Einstein's famous relationship $E = mc^2$. The proton's mass arises not only from the masses of its constituents but also from their energy. In fact, the quarks and gluons bound inside the proton have so much energy that they are moving near the speed of light. Decades of experiments provide a 1D picture of this motion—specifically, how likely we are to find a quark or gluon carrying the fraction x of the momentum carried by the proton. But we know very little about how these same partons move in the plane transverse to the momentum of the proton. We know even less about how these relativistic quarks and gluons distribute themselves spatially. Do these spatial and momentum distributions correlate with the spin of the parton or the parent proton? How do they vary with the parton's longitudinal momentum fraction x or the resolution Q^2 at which they are probed? Ongoing programs at several facilities around the world are actively pursuing answers to these questions. The existing data focus mostly on quarks in the high-x regime; where low-x data exist, we have no information on spin correlations. As shown in Figure 3.12, the EIC will expand the reach of these measurements by nearly two orders of magnitude in x and Q^2. Equipped with the trifecta of high energy, high luminosity, and highly polarized beams, the EIC will open a new frontier in the multidimensional mapping of quark and gluon distributions inside nucleons and nuclei.

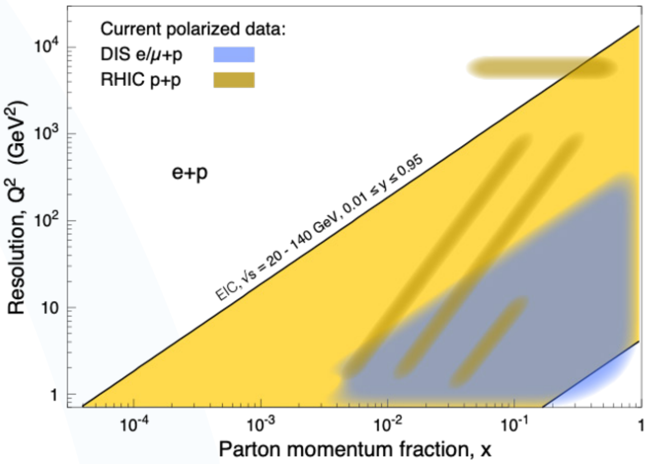


Figure 3.12 The x–Q^2 range covered by the EIC (yellow) in comparison with past and ongoing experiments with polarized beams at CERN, DESY, Jefferson Lab, RHIC, and SLAC (brown and blue) [12].

Elastic and inelastic scattering are examples of processes that can provide information beyond a simple, 1D picture of proton structure. Information about the transverse position of the quarks and gluons that reside inside nucleons and nuclei can be extracted from elastic processes, which can detect the scattered electron and reconstruct the full final state of the proton beam. Inelastic processes, which can detect the scattered electron in tandem with an electro-produced hadron, or jet or pair of hadrons, provide access to the transverse motion of the partons.

These measurements will enable tomography (a series of 2D images) of the nucleon both in transverse position and momentum space. This technique is discussed in Section 3.2.4 and is illustrated in Figure 3.3, with such snapshots stacked along the direction of motion of the parent proton. Starting at large momentum fraction x, in the domain of the valence quarks, and proceeding toward lower x, the regime of the sea quarks and gluons, these images will reveal the locations of quarks and gluons and how their momenta are distributed in the transverse plane. The full richness of transverse momentum information is explored when transverse polarization (with the proton spin direction perpendicular to the direction of motion) is added. In this case, orbital motion leads to correlations between spin and transverse momentum, generating an asymmetric transverse momentum distribution. These images are fully 3D because the 2D transverse momentum distribution is measured as a function of *x*.

Proton tomography will also allow us to gain insight into the origin of the proton mass. For example, by studying the processes of elastic charm–anticharm and bottom–antibottom bound state production near threshold at the EIC, we will be able to extract information that can be related to the distribution of mass inside the proton, known as the gravitational form factors. These form factors can then shed light on the origin of the proton mass and aspects of the QCD trace anomaly, which is the quantum-mechanical mechanism that is fundamental to generating the proton mass. The EIC will provide a unique opportunity to better measure the gravitational form factors by providing a lever arm in Q^2 for elastic production of charm–anticharm and the heavier bottom–an-

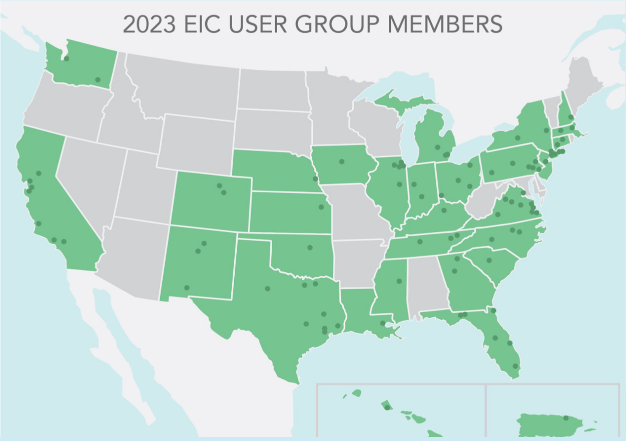
Sidebar 3.8 EIC Network for Discovery Science and Workforce Development

An EIC network would empower discovery science at the EIC while strengthening and building nuclear physics research at U.S institutions, especially those with limited research capacities, and supporting training of a STEM workforce for the nation from a broad pool of talent.

The network would promote partnerships between U.S. national labs and universities and support students and postdoctoral fellows. Additionally, the network would foster collaborations between experimentalists and theorists, organize traineeships, and provide mentoring and career development programs.

In addition to discovery science, the nation benefits from a highly skilled STEM workforce for advances in fields such as energy, environment, health, and national security.

One of our DOE-NP Traineeship (NPT) students, Ambar Rodriguez Alicea. She was an undergraduate at Univ of Puerto Rico, and worked with Luca Cultrera from Instrumentation Division at BNL on "spin polarized electron emission studies", to investigate numerically finding better photocathodes for producing polarized electrons. She is now a graduate student at Michigan State University pursuing a PhD in nuclear physics [S22].



[S23]

[S24]

tibottom bound states. Understanding the origin of the proton mass is an important and fundamental question related to our understanding of the origin of mass in the visible universe.

3.4.1.3. Gluon dynamics in uncharted territory

The strong force is different from the electromagnetic force in a very important way. The gluon—the carrier of the strong force—also possesses color charge. Thus, gluons can interact with each other via the strong force. By contrast, the photon—the carrier of the electromagnetic force—is electrically neutral. Therefore, photons cannot interact with each other, leading to stark differences between hadrons and atoms as strong and electromagnetic bound states, respectively. This unique behavior allows a single gluon to split into two gluons, and those two gluons can split again, producing either more gluons or perhaps a quark–antiquark pair. As the splitting continues, conservation of momentum requires that the daughter gluons and quarks carry smaller and smaller momentum compared with the parent gluon. The reverse can and does happen; that is, these very low-*x* partons may interact and recombine into a single higher-momentum gluon. As a result, the lowest momentum partons flicker in and out of existence and can only be observed for a very short time. Studying these extremely low-momentum partons requires probing the inside of protons and heavy nuclei with very energetic beams of electrons or protons (Figure 3.13). The EIC will be powerful enough to capture the interactions of these extremely low-*x* particles, allowing scientists to view—for the first time—a completely new landscape of gluon interactions.

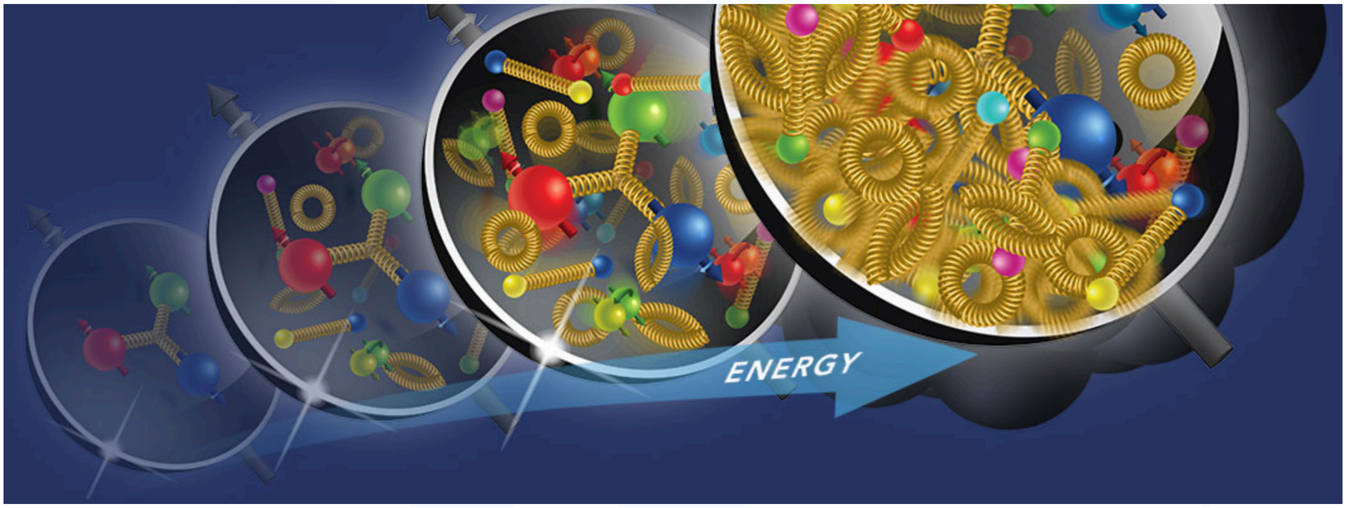


Figure 3.13. As the energy of the electron beam used to probe the inside of the proton increases, a sea of low-x gluons and quark–antiquark pairs becomes visible. *The colored orbs represent quarks and antiquarks, and the gold springs represent the gluons [13].*

This ever-increasing number of low-*x* gluons and quarks is confined within the proton, resulting in an extremely high density of partons. But will this high density keep increasing as we probe to lower and lower values of *x*? Will the nature of strong interactions change in the high-density regime? The growth of the gluon density is expected to saturate at some small value of *x*, leading to the novel regime of gluon saturation. The new dynamics in the saturation regime is due to gluon mergers as mentioned above: the mergers compensate for the splittings, leading to a gluon density that no longer increases as *x* gets smaller. One of the primary scientific missions of the EIC is to discover and explore, both experimentally and theoretically, this new regime of gluon saturation.

A key feature of gluon saturation is the emergence of a momentum scale Q_s, known as the saturation scale. The scale is predicted by a theoretical framework of nonlinear evolution equations, referred to as color glass condensate effective field theory, and designates a transition from the low-density regime ($Q > Q_s$) to the high-density saturated regime ($Q < Q_s$), as indicated in the top panel of Figure 3.14. This theory predicts that the saturation scale will grow both with decreasing *x* and with increasing atomic mass number. The EIC is uniquely designed to test these theoretical predictions and explore this new domain of saturated gluon fields. Unlike other high-energy colliders, the EIC can use beams of electrons, which are well-understood fundamental particles, to probe a wide range of atomic masses at very high energies and therefore very low *x*. Unambiguously establishing this novel domain of QCD and its detailed study is one of the most ambitious and exciting goals of the EIC.

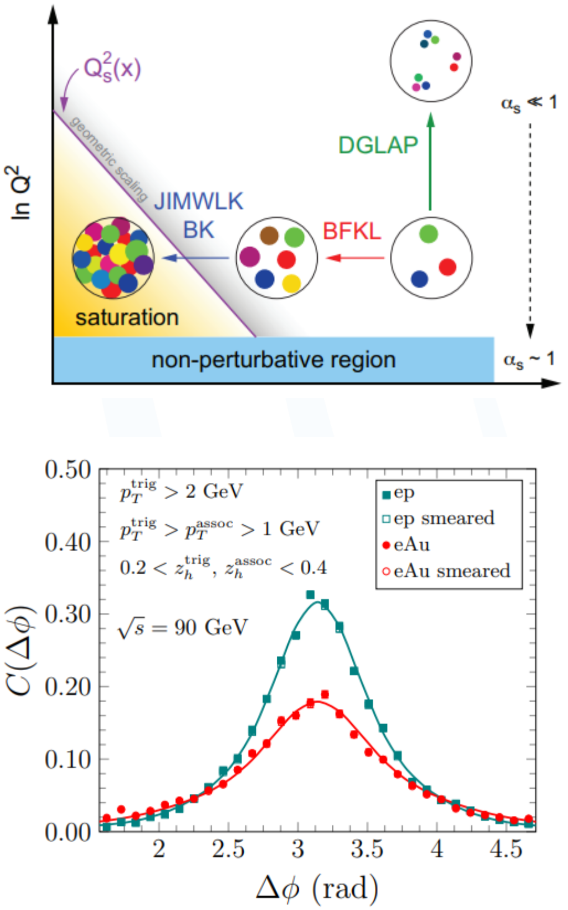


Figure 3.14. Evidence for gluon saturation. *(top) Schematic illustration of the probe resolution,* Q^2 *as a function of x, indicating the saturation region in yellow and transitions to the low-density regime. Theoretical color glass condensate calculations will provide predictions and interpretation of experimental data for all regions outside of the nonperturbative blue box. (bottom) A saturation model prediction of the hadron–hadron correlation function C(Δϕ) to be measured at the EIC, plotted versus their azimuthal angular separation Δϕ. The peak at Δϕ = π decreases as collisions change from electron–proton to electron–gold collisions because of the increase in the saturation scale with atomic mass number [14].*

A definitive discovery of gluon saturation will require the observation of multiple experimental signatures. The EIC program will follow a multipronged approach that leverages the versatility of the collider and the large-acceptance ePIC detector. Day-one measurements include the proton and nuclear structure functions, which are proportional to the gluon density and thus sensitive to saturation physics. Another observable result is the suppression of dihadron angular correlations in electron–ion collisions. This suppression is illustrated by comparing the red and green curves in Figure 3.14 (bottom). The green curve represents electron–proton scattering, and the red curve shows the suppression in electron–gold scattering from gluon saturation effects. Additionally, the EIC will measure diffractive particle production as another promising avenue to establish the existence of saturation and to study the underlying dynamics. Diffraction is unique in that it requires the exchange of a color-neutral object, typically a pair of gluons, between the virtual photon emitted by the electron and the remnant of the interacting proton. Diffractive cross sections are very sensitive to the onset of nonlinear dynamics in QCD, and an early measurement of coherent diffraction by the EIC would provide the first unambiguous evidence for gluon saturation.

3.4.1.4. Nuclei: not just collections of protons and neutrons

A central question of nuclear physics is how and why the distribution of quarks and gluons changes inside a proton when that proton is bound inside a nucleus. The EIC will address this question using high-energy collisions to make precision measurements of the nuclear modification of PDFs with resolution that is not possible with current technology. PDFs describe the internal structure of the proton by characterizing the probability of finding a certain flavor of quark or gluon at a specific momentum fraction *x* and resolution Q^2. The EIC will allow for the study of the differences between PDFs of bound and unbound nucleons with unprecedented precision.

These differences are often studied by extracting the ratio of the nuclear PDF, divided by the total number of neutrons and protons in the nucleus, to the proton PDF. One might expect this ratio to be one (i.e., that the distribution of quarks and gluons is the same inside free protons and ones bound inside the nucleus). In fact, that is not the case: as illustrated in the top panel of Figure 3.15, the nuclear modifications described by such a ratio are suppressed at low and high *x*, the so-called shadowing and EMC regimes, and enhanced in the antishadowing region at moderate *x*. Measurements of nuclear PDFs elucidate the extent to which a nucleus could be described by a collection of independent nucleons—a fundamental question about nuclear properties in QCD. The effect of the EIC data on our knowledge of the nuclear gluon distribution function is shown in the bottom panel of Figure 3.15, where the relative error bars clearly shrink as future data from the EIC are incorporated. The EIC provides broad coverage, fully mapping the shadowing and antishadowing regimes, as well as part of the EMC regime.

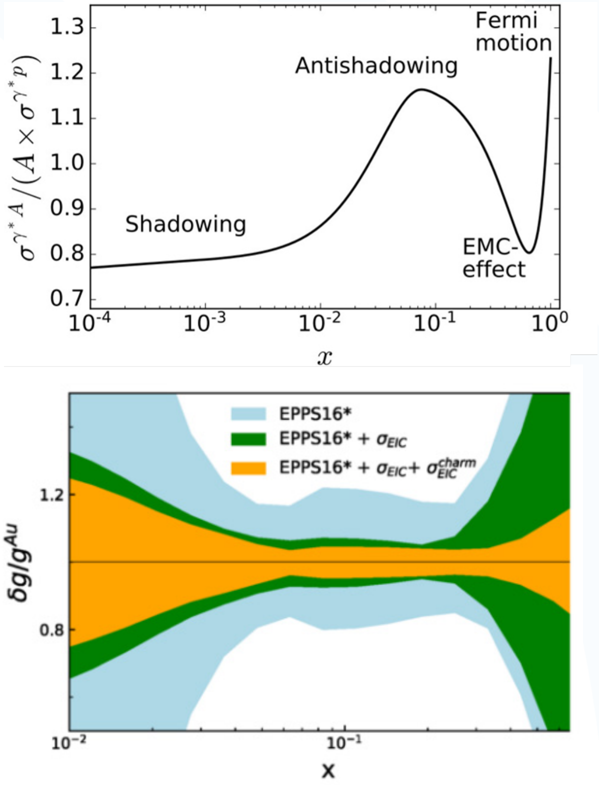


Figure 3.15. The differences between bound and unbound nucleons. *(top) The cross section ratio $\sigma^{\gamma*A}/(A\ \sigma^{\gamma*p})$ measures the nuclear modification of the parton distribution functions. (bottom) Relative uncertainty bands of the gluon density for gold at $Q^2 = 1.69\ \text{GeV}^2$. The blue band is the original EPPS16* fit, the green band incorporates planned inclusive cross section EIC data, and the orange band also adds the charm cross section σ^{charm} [15].*

The EIC will also provide novel insight into the physics of how protons and neutrons in nuclei interact with each other and how their interactions in turn relate to the nuclear force. Using far-forward tagging techniques to detect protons and neutrons that have been ejected from the nucleus, the EIC will disentangle the influence of the strong nuclear interaction on the bound nucleon structure. Extending the free-nucleon structure program to bound nucleons via spectator tagging techniques is a novel frontier that presents both experimental and theoretical challenges, as it requires performing high-precision measurements, which the EIC can uniquely provide.

3.4.1.5. Hard probes in cold nuclei

The EIC will significantly expand our understanding of hadron formation inside nuclear matter (Sidebar 3.3). Studying hadronization for light and heavy quarks in cold nuclear matter can unravel some of the mysteries surrounding energy loss in QGP (Section 3.3). The wide range of Q^2 provided by the EIC is critical for these studies, elucidating how the transformation of quarks and gluons into visible and detectable particles changes as the density of nuclear matter increases. Multiple mechanisms may contribute to the evolution of these modifications caused by hadronization. The high luminosity provided by the EIC will enable collecting the large datasets required to untangle these contributions (Figure 3.16). Studies at the EIC will provide direct experimental input for constraining the evolution of parton splitting functions in nuclear matter.

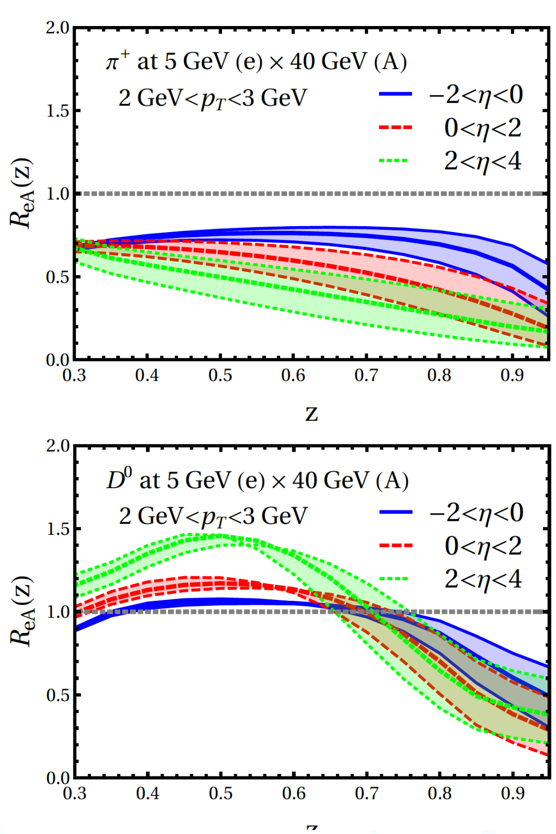


Figure 3.16. Predicted ratio of relative particle production (N_h/N_{incl}) in eA scattering over that in ep as a function of z, the momentum fraction of the parton carried by the respective hadron. *Pions (top), which are light, show the largest nuclear suppression at the EIC. However, heavy flavor meson ratios (bottom) can differentiate models of hadronization since they show a substantially different modification in eA [16].*

3.4.1.6. Physics beyond the standard model

The Standard Model of particle physics is a wildly successful framework that describes all 17 known fundamental particles and 3 forces in the universe (except gravity). Although the Standard Model has been tested and shown to be correct to parts-per-trillion precision, it still cannot explain several key characteristics of the universe: for example, the origin and nature of dark matter and the asymmetry of matter and antimatter. Physicists and astronomers from all areas of the field (Chapter 6 discusses ongoing programs within nuclear physics) are joining the hunt for new particles and forces that may explain the origin of these mysteries. The intense polarized electron and hadron beams available at the EIC, combined with the wide acceptance of the ePIC detector, provide unique opportunities for a variety of experiments that are sensitive to physics beyond the Standard Model (BSM).

Many theories propose new BSM mechanisms. One is the prediction of a dark force carrier, the dark Z boson. Precision measurements in regimes available only at the EIC will provide limits on the mass range

Sidebar 3.9 Parity-Violating Electron Scattering: A Versatile Tool to Explore Hadrons, the Standard Model, and Neutron Stars

CEBAF's primary mission is to study the strong interaction, but the special properties of its electron beam facilitate uniquely precise measurements of parity-violating electron scattering (PVES) asymmetries (Figure 1). Measurements of such asymmetries, often as small as parts per million or parts per billion, affect a variety of fields, including hadronic physics, astrophysics, particle physics, and nuclear astrophysics.

From neutron-rich nuclei to neutron stars

A feature of heavy nuclei, which tend to be neutron rich, is that the densely packed protons occupy slightly smaller volumes than neutrons, causing a "neutron skin" in a heavy nucleus. The thickness of this skin is sensitive to the equation of state for nuclear matter (Chapter 4), providing a terrestrial laboratory to study the behavior of the extremely dense nuclear matter contained within neutron stars. The nuclear neutron skin thickness—measurable via PVES because the neutron carries a much larger weak charge than the proton—can be correlated to inferred neutron star properties from binary neutron star mergers and x-rays from pulsars. The two high-precision PVES measurements at Jefferson Lab show that the neutron skin of lead-208 (Figure 2) appears thicker than expected, whereas that of calcium-48 is thinner, presenting an empirical challenge to precise modeling of nuclear structure and motivating further experimental and theoretical investigations.

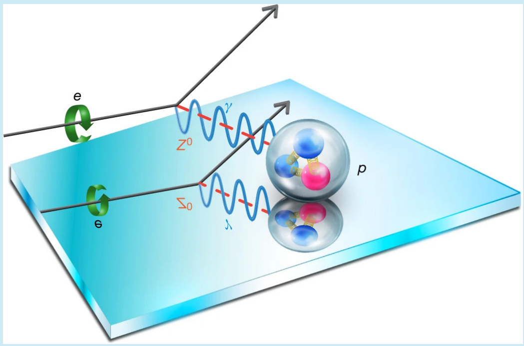


Figure 1: The weak interaction causes a difference between scattering left-handed electrons and its mirror image, scattering of right-handed electron [S25].

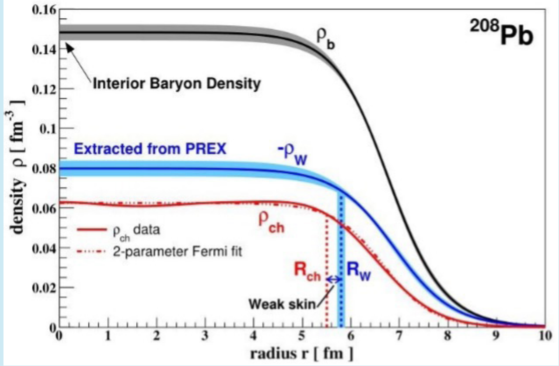


Figure 2: Weak (blue) and baryon densities (black) of lead-208 from the combined Lead Radius Experiment (PREX) datasets, with uncertainties shaded, are compared with the charge density (red) [S26].

Searching for Physics Beyond the Standard Model

The recent Qweak experiment at Jefferson Lab measured the parity-violating asymmetry in elastic electron proton scattering and extracted for the first time the proton weak charge at the 6.3% level, leading to a determination of the weak mixing angle, a fundamental parameter of the Standard Model (Chapter 6). The future Jefferson Lab program will comprise two experiments that will advance our knowledge of physics beyond the Standard Model: MOLLER will measure the electron's weak charge and determine the weak mixing angle with a precision comparable to high-energy collider experiments, and SoLID PVDIS will uniquely access a precise electron-quark coupling that probes the parity-violating nature of quarks. The accuracy envisioned for SoLID PVDIS will also enable precision probes of the nucleon's partonic structure, including the down to up quark PDF ratio of the proton and the dynamic origin of the nuclear EMC effect of calcium-48.

of possible dark Z bosons. The constraints placed by these measurements will be unique and complementary to ongoing measurements at the LHC and at Jefferson Lab (Sidebar 3.9). The EIC also can explore another signature of BSM physics: the charged lepton flavor violation (CLFV), specifically the conversion of an electron into its much heavier cousin, the tau lepton. CLFV is mediated by a new set of BSM particles called leptoquarks, and the electron–tau conversion channel would be sensitive to the difference between different types of leptoquarks. This conversion is one of the most promising CLFV channels to be studied at the EIC because of the facility's high beam luminosity and the exquisite vertex resolution provided by the ePIC detector. The limits placed by the EIC could surpass existing limits set by past experiments. Finally, the spin polarized electron beams provided by the EIC would provide a unique sensitivity to detecting axion-like particles, a different type of BSM particle that may also be produced in electron–tau conversion.

3.4.1.7. EIC Theory Alliance—a new force for support and change

EIC theory includes many interdisciplinary components best addressed through a broad alliance. The main scientific thrusts of the EIC Theory Alliance (EIC-TA) include gluon saturation and small-*x* physics; exclusive processes and general parton distributions; semi-inclusive processes and transverse momentum distributions; jets, heavy flavor, soft collinear effective theory and hadronization; nucleon spin and the precision electron–proton frontier; global analyses with AI/ML; exotic hadron spectroscopy; tests of fundamental symmetries; and nuclear structure. Many disciplinary and interdisciplinary connections exist between these topics. For example, lattice QCD is an integral component of many of the physics areas. AI/ML techniques may play an important role in the global analysis combining experimental and lattice data and in developing more efficient algorithms for lattice QCD calculations.

The EIC-TA is envisioned to be a decentralized organization that will provide funding for graduate students, postdocs, bridge positions at universities, and visiting positions. Alliance membership will be free and open to all who wish to join, both domestic and international, at all career levels. The EIC-TA will organize topical schools and workshops. The promotion of a welcoming and inclusive EIC theory environment will be embedded in the organizational structure to ensure that the future EIC theory workforce is diverse and sustainable.

The EIC-TA will raise the visibility of EIC-related theory and obtain the resources needed for adequate support of the EIC, including for workforce development. The long timeframe of EIC construction (>10 years), combined with the prospect of decades of operation, requires a strategic plan to ensure a robust program is in place. Targeted funding of a theory alliance, in addition to the base theory funding, throughout the lifetime of the facility, is an excellent way to achieve these goals.

Enormous progress has been made since the last Long Range Plan toward understanding the valence structure of the proton and neutron. With the EIC, we will finally be able to study the contributions of gluons and sea quarks to the building blocks of the nucleus. A new era of discovery is within our reach.

4 NUCLEAR STRUCTURE AND NUCLEAR REACTIONS

Atomic nuclei make up 99.9% of the visible universe by mass. Nuclear properties and reactions are protagonists in the evolutionary drama of the cosmos, from the first moments after it began with the Big Bang, to the birth and development of stars through their lives, to violent showdowns such as supernova explosions and neutron star mergers. Nuclei are made of tens, or even hundreds, of neutrons and protons whose interactions, structure, and dynamics are governed by the interplay of three of nature's fundamental forces: the strong and weak nuclear interactions and electromagnetism. These forces produce a tremendous diversity and complexity of nuclear phenomena. These phenomena include ordered patterns, such as the organization of neutrons and protons into shells much like electrons in an atom; regular sequences of energy levels caused by rotations and vibrations that involve many, if not all, nucleons acting together; and clustered states in which protons and neutrons group into substructures.

The primary goal of QCD is to understand the interactions of quarks and gluons as constituents of matter, while nuclear structure and reactions is focused on the combined behavior of neutrons and protons in atomic nuclei. The core objectives of the nuclear structure and nuclear reactions fields are to arrive at a predictive understanding of the properties of atomic nuclei, the limits of their existence, and their behavior in nuclear decays and reactions. Fulfilling these objectives is the overarching goal that drives this field. This science also reveals how nuclei and nuclear reactions operate in the universe to determine the life cycle of stars and the chemical evolution of the cosmos (Chapter 5, "Nuclear Astrophysics"), allows nuclei to be used as laboratories for testing nature's fundamental symmetries and laws (Chapter 6, "Fundamental Symmetries"), and provides core nuclear data for applications that benefit society (Chapter 11, "Applications"). The influence of the quarks and gluons on nuclear building blocks (Chapter 3, "Quantum Chromodynamics") is fundamental to our science.

Building on the considerable progress made since the last Long Range Plan in 2015, the low-energy nuclear physics community looks at the next decade with great optimism and excitement. The field of nuclear structure and reactions is at the brink of a new age of discovery with exciting opportunities at the newly operational FRIB, upgrades to the ATLAS facility, the complementary unique capabilities of the university-based laboratories, and the staggering advances in nuclear theory and computation. The optimal operation of US national and university facilities, a healthy and robust experimental and theoretical core research program, and the pursuit of upgrades and new instruments are now needed to capitalize on the investments in the field to accelerate progress toward answering the broad science challenges and goals of nuclear science.

Success in this endeavor necessitates drawing on talent from the entire nation—and across the world—so a welcoming nuclear structure and reactions community is central to this vision (Sidebar 4.1).

4.1 WHAT ARE THE LIMITS OF NUCLEAR EXISTENCE?

The nuclear chart is the 2D landscape in which isotopes are organized as a function of their number of neutrons, N, and protons, Z. It extends from hydrogen ($Z = 1$) to the rare superheavy elements ($Z > 102$). To determine the chart's horizontal extent, we need to know how many isotopes can exist for each element, answering the intriguing and basic question at the heart of nuclear physics: Which combinations of protons and neutrons are bound by the strong force to produce a nucleus? This question has only been firmly answered for light elements up to neon ($Z = 10$).

The need to understand the forces that hold a nucleus together motivates the experimental and theoretical exploration of the limits of nuclear existence: the maximum number of neutrons that can be added to the nucleus of a given element before the proton–neutron asymmetry becomes untenable, and the minimum number of neutrons needed to bind the nucleus in the presence of the Coulomb repulsion of the protons. The very last bound isotopes along the neutron-rich and neutron-deficient fringes of the chart define the neutron and proton driplines.

The proton dripline, illustrated in Figure 4.1, lies quite close to the narrow band of stable isotopes that runs near the center of the nuclear chart—the so-called valley of stability—and is well charted. The scientific challenges for both experiment and theory lie in producing and modeling the most neutron-rich nuclei that can exist. Recent highlights of isotope discovery were the first observations of sodium-39 and calcium-60 and the non-observation of neon-35 and neon-36 at the Institute of Physical and Chemical Research (RIKEN) facility in Japan. Intriguingly, for $Z = 20$, the recent discovery of calcium-60, together with theoretical predictions, suggests that the calcium isotopes may exist out to calcium-70 with 50 neutrons. On the theory side, excellent progress has been made toward understanding the neutron dripline using both first-principles and mean-field calculations. Both approaches now quantify uncertainties and predict the limits of existence on a statistical basis. Nevertheless, the challenge is that predictions of the neutron dripline at, for example, calcium-70 are a distant extrapolation given that the last calcium isotope proven to exist is calcium-60.

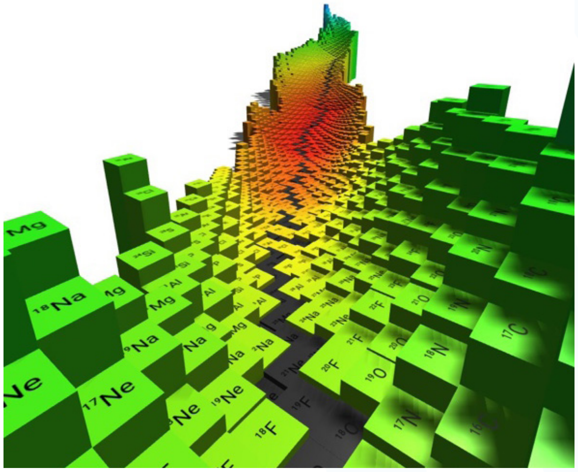


Figure 4.1. The chart of nuclides, showing the limits of bound and unbound nuclei. *What are the limits of nuclear existence? We don't know the boundaries: how far we can go adding protons (left side) or neutrons (right side) before we hit the driplines. At these driplines the nuclear force is no longer able to bind additional nucleons to the nucleus. Along the valley of stability (dark grey), the limits of nuclear existence appear as rising colored walls. FRIB will be able to establish the neutron dripline beyond Z=10 (neon), possibly reaching it up to Z=30, while FRIB400 would double the reach to Z=60 [17].*

During the next decade, FRIB will reach the neutron dripline beyond magnesium (Z = 12) and will allow exploration of calcium isotopes out to calcium-66. The energy upgrade of FRIB to FRIB400 would double the facility's reach toward the neutron dripline up to Z = 60 and could even permit the production of cacium-70 if it exists. Confronting predictions of the limits of existence with data from FRIB will provide a stringent test of our understanding of nuclei. Predictive theory in this realm is critical for improving models of the rapid neutron capture process, or r-process, that forged elements beyond iron and of the crystals of neutron-rich atoms in the neutron stars' crust.

4.2 WHAT FEATURES ARISE NEAR THOSE LIMITS AND BEYOND?

The neutrons in nuclei near the dripline are weakly bound, and their behavior differs from that in stable isotopes. Neutrons in these nuclei barely cling to the nucleus, rendering invalid the established theories about how nuclear sizes and shells composed of neutrons and protons scale with mass number. This failure puts our understanding of nuclear forces to the test. New exotic forms of radioactivity emerge, and the structure and reactions of nuclei are closely tied. For example, nuclear reactions involving unstable helium-8 nuclei produced what appears to be an almost-bound state of four neutrons: a tetra-neutron. Conventional models of the forces between neutrons struggle to explain an almost-bound tetra-neutron state. Consequently, additional experiments and theory innovations are advancing our understanding of neutron halos—barely bound isotopes made of neutrons orbiting a compact nuclear core at a distance—that occur at and beyond the edge of nuclear stability. In the next decade, neutron halos will be investigated in medium-mass nuclei at FRIB, and more surprises will certainly occur.

For example, in beryllium-11, the seventh, barely bound neutron sits far from the four protons, forming a halo. Recent studies of a very unusual decay mode of beryllium-11 demonstrate the synergistic efforts within the ecosystem of complementary experimental facilities, motivated and interpreted by theory. The beryllium-11 transforms via beta-decay into a system with energy above the proton-emission threshold of boron-11, causing the decay product to decompose into beryllium-10 and a proton. Initial indirect measurements of this rare process at the European Organization for Nuclear Research (CERN) indicated an unexpectedly high rate of decay, while a novel US-led measurement at Canada's Particle Accelerator Centre (TRIUMF) achieved the first direct detection of the emitted proton from the decay. Two further experiments at Florida State University (FSU) and the National Superconducting Cyclotron Laboratory (NSCL), together with substantial theory efforts, revealed that the unusual decay occurs because of a previously unknown metastable state of boron-11.

We have more knowledge of nuclear dynamics near the proton dripline than we do for neutron-rich nuclei. However, surprises remain on that side of the nuclear chart, such as the discovery of magnesium-18, which disintegrates via emission of four protons right after its formation. Measurements at ATLAS clarified the nature of the ground state of the heaviest one-proton emitter, bismuth-185, and future measurements there will continue to characterize other heavy, weakly bound nuclei.

A highlight from nuclear theory is the description of two-proton emission via a novel three-body treatment of this complex nuclear decay mechanism. Heavier nuclei that are unbound against two-proton emission but have longer lifetimes display the phenomenon of two-proton radioactivity. Experiments at FRIB can explore the resulting proton correlations with unprecedented precision, using instruments such as the FRIB

Decay Station or 3D optical detection, thus supplying data that will challenge these novel calculations.

A powerful way to develop a predictive understanding of the changes in nuclear structure that occur near the driplines is to track how nuclear properties evolve for a particular element as the neutron number increases, from the proton to the neutron dripline, passing through the valley of stability. Such a strategy leads to new discoveries and provides invaluable validation data for nuclear models. Data on elemental chains come from a range of capabilities present in the field afforded, for example, by the charged particle, neutron, electron spectrometers, and mono-energetic photon beams combined with accelerators underground along with spectrometers and novel detectors housed at different ARUNA facilities. Precision data near stability and in selected regions of unstable nuclei are enabled by the high-intensity stable beams of ATLAS and by this facility's upgrades: nuCARIBU, the *N* = 126 factory, as well as the multiuser upgrade. FRIB and dedicated instrumentation such as the High Rigidity Spectrometer (HRS), Gamma-Ray Energy Tracking Array (GRETA), and the Isochronous Spectrometer with Large Acceptances (ISLA) will push this endeavor toward the driplines, and the FRIB energy upgrade will enable increased scientific reach.

A recent example is the exploration of the nickel isotopic chain, highlighting the powerful synergy of complementary experimental capabilities, starting with the study of the stable nucleus nickel-64. Measurements at ATLAS, TUNL, and two European facilities hinted at an unexpectedly complex landscape of coexisting nuclear shapes. Experiments at NSCL tracked this shape coexistence for nickel-68, nickel-70, and nickel-72 and the Radioactive Isotope Beam Factory (RIBF)/RIKEN showed that shape coexistence may prevail at the key doubly magic nucleus nickel-78. Nickel isotopes with even more neutrons will be accessible at FRIB, pushing these investigations into the regime of weak binding. Nickel-84 and nickel-86 are predicted to have neutron skins thicker than 0.5 fm: nickel-84 is within reach of FRIB and the HRS, but heavier nickel isotopes require FRIB400. The neutron-generator upgrade to the Californium Rare Isotope Breeder Upgrade (nuCARIBU) and the *N* = 126 factory at ATLAS offer novel opportunities to explore the nuclear structure along the tin isotopic chain and for slightly lighter elements than the magic nucleus lead-208. Calculations of nuclear properties based on first principles have progressed to such heavy systems and will pave the way toward understanding the driving forces of structural change.

4.3 WHAT ARE THE HEAVIEST NUCLEI THAT CAN EXIST?

At the other extreme of the chart of nuclides, new elements and new isotopes have been discovered. Superheavy elements ($Z > 102$) are teetering at the limits of mass and charge. Their existence is governed by a delicate balance between the attraction of the nuclear force and the intense repulsive Coulomb force of their many protons. As such, they constitute a sensitive and fertile testing ground for nuclear models.

In superheavy territory, four new elements (Z = 113, 115, 117, and 118), shown in Figure 4.2, were added to the periodic table at facilities abroad, with US contributions and leadership from Lawrence Livermore National Laboratory (LLNL), and Oak Ridge National Laboratory (ORNL). Meanwhile, the first direct determination of the mass number *A* of a superheavy element was accomplished at LBNL.

The prospects for the future are tantalizing. A concerted US effort on the horizon will attempt the production of new elements at LBNL. The discovery of new elements—new nuclei with a proton number higher than anything ever formed—together with the

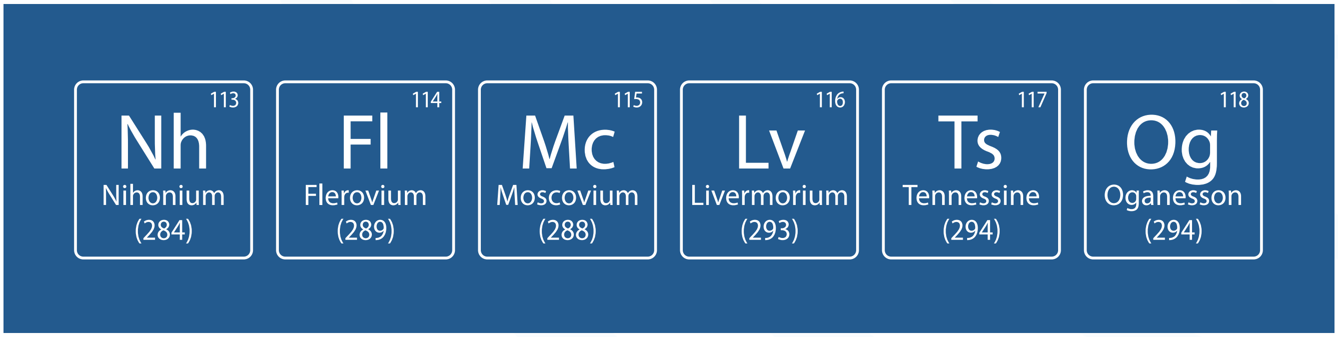


Figure 4.2. Since the 2015 Long Range Plan, elements in the last line of the periodic table were created and named. *In the next decade, will we see the end of the road for elements? Theory estimates claim that elements up to Z = 174 are possible. Current focus is on the search for element Z = 120 [18].*

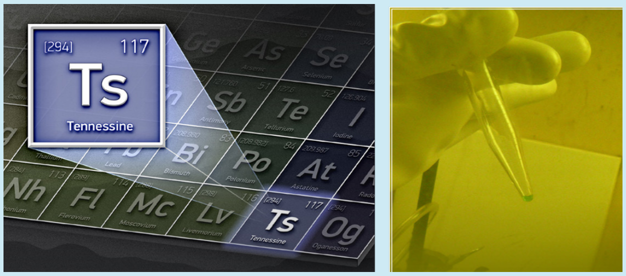
examination of their structure by studying their decays and the determination of their properties can ascertain their location in the periodic table and anchor them to the rest of the chart of nuclides. Achieving such a discovery will require investments in target technologies and dedicated beam time.

The next decade will provide a glimpse of the structure of the heaviest nuclei that can exist. Joint efforts at LBNL, ATLAS, and various university laboratories, including Texas A&M University (TAMU) and Notre Dame (ND), will explore the role of reaction mechanisms, nuclear fission, and cluster emission for the heaviest elements and simultaneously probe the structure of these nuclei via gamma-ray spectroscopy.

4.4 HOW DOES THE NUCLEUS CHANGE AS IT IS EXCITED TO HIGHER ENERGIES, AND WHAT PHENOMENA EMERGE?

When a nucleus is excited via a reaction or decay and particle emission is not possible, the nucleus transfers that energy to motion. Many nucleons may be excited collectively, leading to phenomena such as a vibration and/or rotation of the whole nucleus. The identification and characterization of nuclear excited states enable the study of these emergent collective behaviors, which can deform the nucleus's shape and allow multiple nuclear shapes to coexist within the same nucleus (Figure 4.3).

Sidebar 4.1 Examples of International Collaborations in Our Field



The discovery of element 117, Tennessine. Left: Element 117 filled the remaining square on row seven of the Periodic Table. Right: Oak Ridge National Laboratory produced 22 mg of berkelium-249 for the element 117 experiment [S27-28].

Forging New Elements—the Discovery of Tennessine

Nuclear science is inherently international, and the search for new elements is no exception. In 2017, a large international collaboration of scientists used detectors and facilities in Europe, electronics and rare heavy isotopes from the United States, a lot of time and patience, and technical knowledge from researchers around the world to produce a completely new element: element 117, Tennessine. Next-generation superheavy element searches are built on these international collaborations, harnessing US-sourced materials at facilities in Japan, Germany, France, and elsewhere.

The International Research Network for Nuclear Astrophysics (IReNA), supported by the NSF, brings together nuclear physicists, astronomers, and computational scientists to answer a long-standing question: Where do the elements that make up our world come from?

IReNA connects nine interdisciplinary research networks across four continents to foster collaboration and complement and enhance research capabilities in the United States and abroad. A central focus is training students and other young researchers in a unique interdisciplinary, collaborative, and international environment that prepares them for a broad range of STEM careers.

Artist representation of IReNA network [S29].

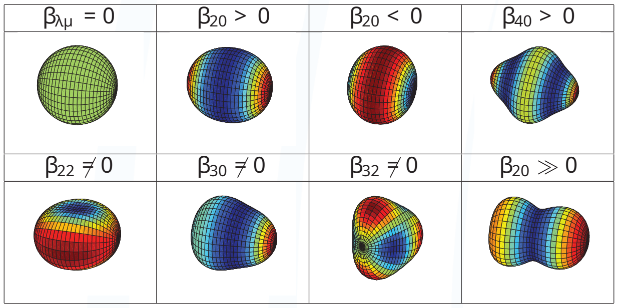
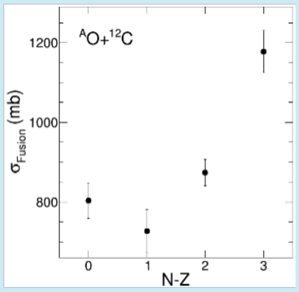


***Figure 4.3. Various possible shapes of nuclei.** These shapes are exaggerated for visual clarity [19].*

The significant effort dedicated to such studies not only at US user facilities but also at the ARUNA laboratories (Sidebar 4.2) has yielded remarkable progress. However, the question of how excited states in medium-mass nuclei evolve toward the limits of existence remains open. Spectroscopy with GRETA and the FRIB Decay Station (FDS) will provide first excitation energies in some of the most neutron-rich nuclei, and FRIB400 will significantly increase the reach of such studies.

Pear-shaped nuclei are predicted to exist in select regions of the nuclear chart (e.g., in the neutron-rich barium isotopes that can be measured at ATLAS' upgraded nuCARIBU facility). Pear-shaped deformation will enhance the signal in the search for a permanent atomic electric dipole moment, which—if discovered—will be key to unraveling the mystery of the matter–antimatter asymmetry in the universe (Chapter 6, Sidebar 6.2). This study highlights the synergy

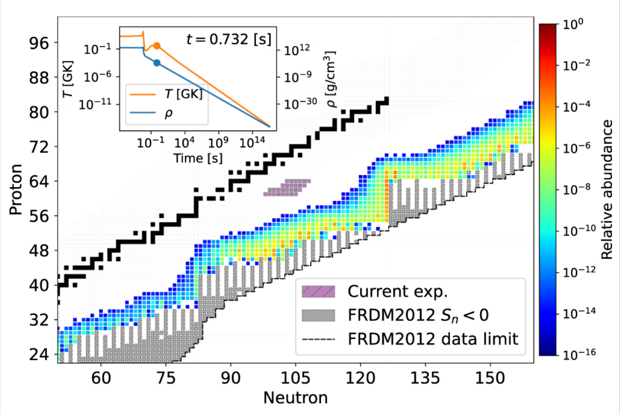
A large increase in the fusion cross section for neutron-rich nuclei could signal decoupling of protons and neutrons in a nucleus. Using a compact and portable experimental setup, systematic measurements can be made at facilities around the world. Small research groups travelling with cutting-edge instruments and collaborating to conduct experiments internationally are important elements of research in the field.



Fusion cross sections of oxygen and carbon as a function of the number of excess neutrons [S31].

Collaboration led by Romualdo deSouza, Indiana University [S30].

Recent results from a large international collaboration studying the decay properties of very exotic nuclei at RIKEN in Japan have started to probe the effects of these nuclei on r-process nucleosynthesis. These new experimental results relied on specialized detectors developed in the United States for the study of beta decay and beta-delayed neutron emission, critical processes in the production of very neutron-rich nuclei in the cosmos.



Snapshot of the r-process path in a neutron star merger scenario. Grey boxes indicate nuclei that are unbound. Purple boxes show the isotopes measured in the BRIKEN campaign [S32].

Members of the BRIKEN collaboration [S33].

between research on nuclear structure, nuclear reactions, and the studies of fundamental symmetries.

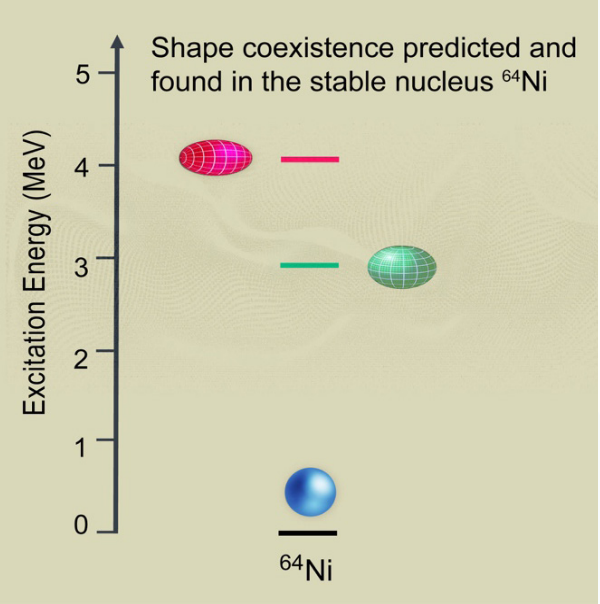


Figure 4.4. The evolution of the nuclear shape in stable nickel-64 as predicted by large-scale nuclear model calculations. *Now, new research has confirmed the coexistence of three nuclear shapes [20].*

Meanwhile, the study of very elongated shapes in nuclei provides a window into nucleonic shell structure at large deformation. Extensive work earlier this century enabled the characterization of nuclear shapes with 2:1 axis ratio. In the coming decade, GRETA at ATLAS is poised to enable the discovery and study of structures with even bigger deviations.

Another type of extreme deformation is that resulting from large-amplitude collective motion. Nuclear fission is a principal and important example of this deformation. Much progress toward better models of fission has been made during the last several years, but it still remains one of the most challenging quantum many-body problems. Understanding fission has far-reaching implications for the r-process, nuclear energy, national security, and nonproliferation applications. For example, at TUNL/HIγS, neutron- and photo-induced fission on long-lived targets will provide precision studies of this complex process, and FRIB and FRIB400 will enable unique fission studies of the shortest-lived heavy nuclei with correlated fission fragments simultaneously detected in the HRS.

4.5 HOW DOES MATTER BEHAVE AT THE MOST EXTREME DENSITIES IN THE UNIVERSE?

The atomic nucleus is 100 trillion times denser than water. The way that the constituent protons and neutrons arrange themselves inside the nuclear volume is specified by how much pressure nuclear matter can support at a given density: a relationship known as the nuclear equation of state (EOS). The EOS determines the thickness of the neutron skins of heavy nuclei, where an excess of neutrons collects near the nuclear surface (Sidebars 3.9, 5.2). It governs not only the properties of heavy nuclei and their collisions, but also those of neutron stars and their mergers.

A quantity called the symmetry energy describes the energy cost of nuclear matter having an imbalance between protons and neutrons. How this symmetry energy depends on the nuclear density is a key open question in the field of nuclear science. At and below the typical density encountered in heavy nuclei, the symmetry energy has been well constrained by several different observables, including nuclear masses and neutron-skin measurements. Heavy-ion reactions with high-intensity stable beams at TAMU have been particularly effective, probing the equilibration of protons and neutrons during the collision. They will continue to be critical to elucidate the detailed anatomy of heavy-ion collisions. A great deal can be learned by measuring how nuclear matter responds to being compressed in the collision of the two nuclei.

However, at the higher densities that are important for understanding the structure and mergers of neutron stars, the symmetry energy is not as well constrained. Only a few experiments using the collisions of two heavy ions at high energies have been used to access these densities. Recent highlights are the determination of the symmetry energy for asymmetric matter using heavy-ion collision experiments at RIBF/RIKEN (US-led) and the GSI Helmholtz Centre for Heavy Ion Research (GSI).

These experiments set initial limits on the density dependence of the symmetry energy. The rather large uncertainty of such limits will be greatly reduced by employing the more asymmetric collision systems available at FRIB. Ultimately, FRIB400 can compress asymmetric nuclear matter to twice normal nuclear density, an important capability for understanding neutron stars. This momentous experimental opportunity must be matched by progress in theory: advanced models of the complex collisions would be a game changer.

4.6 WHAT HAPPENS WHEN NUCLEI COLLIDE?

Such studies of asymmetric nuclear matter are just one example of the powerful lens provided by nuclear reactions. Nuclear reactions allow us to peer into the properties of nuclei; and reactions are central to understanding processes that power stars and explosive events in the universe. A variety of nuclear

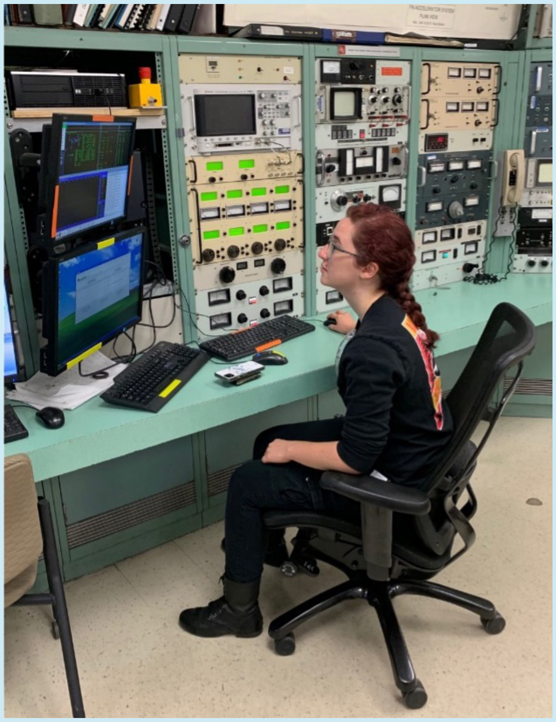
Sidebar 4.2 Collaboration Enabling New Science and Opportunities

FIREBALL

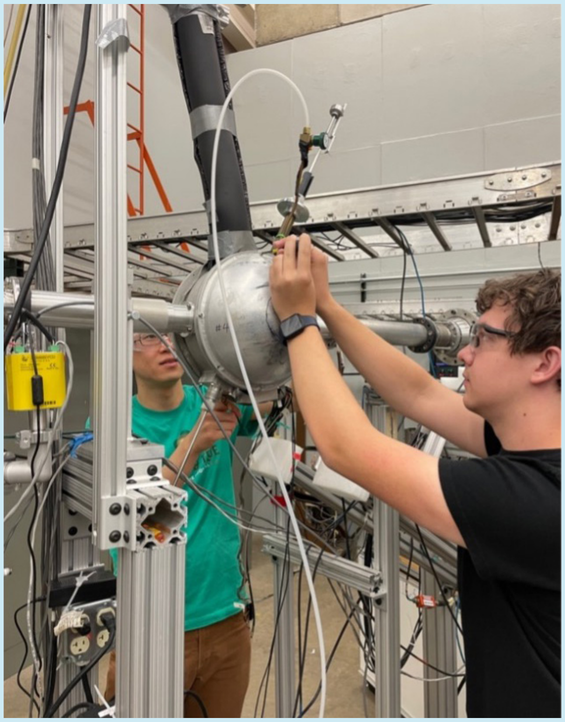
Nuclear physics is a collaborative effort. This is borne out in the collaboration between a primarily undergraduate institution—University of Wisconsin La Crosse (UWL), an ARUNA laboratory—The University of Notre Dame (ND) Nuclear Science Laboratory (NSL), and a National Laboratory—Lawrence Berkeley National Laboratory (LBNL). Scientists at UWL and ND were awarded a National Science Foundation Major Research Instrumentation grant to build the Internal Conversion Electron Ball (fIREBall) Array at the NSL. This detector array will detect high-energy electrons in coincidence with gamma rays, contributing to a variety of open questions in nuclear science, including nuclear astrophysics, theoretical models in light nuclei, and low-lying levels and various degrees of freedom in deformed nuclei. The project also contributes to the national workforce by training undergraduate and graduate students in detector techniques, troubleshooting, data gathering, and analysis. These skills are all transferable to careers that advance national health, welfare, and national security.

Once funding was secured, the lithium-drifted silicon (Si(Li)) detectors were unavailable commercially. LBNL scientists applied newly developed techniques to grow and build the required thick silicon detectors. Because of this project, this technology is now available worldwide.

This project enables exciting science while training young scientists and providing the nation with a new source of highly sought-after detectors. The fIREBall spectrometer is the only one of its kind in the USA and will help to answer one of the outstanding challenges in nuclear structure.



UWL undergraduate student Hannah Bechtel on shift at ND.



Kevin Lee (graduate student ND) and Nicholas Raden (undergraduate student UWL) work on fIREBall (above) [S34-36].

science applications, ranging from stockpile stewardship and nuclear energy to medicine and industry, also rely on reactions.

In a reaction, a projectile and a target undergo a close encounter that can be slower or faster, depending on their relative speed. This encounter is also sensitive to the masses and internal structure of the nuclei involved, and all these parameters can yield very different outcomes. For example, at the lowest kinetic energies (and hence speeds), a collision partner may capture a single nucleon or an alpha particle, akin to processes that occur in stellar environments. At somewhat higher energies, the nuclei may fuse and form a much heavier system, a reaction that is used in the laboratory to create the heaviest elements of the periodic table. At yet higher energy, one or several nucleons may be transferred between projectile and target, a sensitive probe of the nuclear many-body system. At the highest energies, nuclei may disintegrate in a head-on encounter and their debris give a glance of bulk properties of nuclear matter; or they may graze each other and only a single nucleon may be knocked out, revealing information about their internal structure. Yet other collisions release energy via the fusion of light nuclei and fission of heavy nuclei.

Since the last Long Range Plan, this full spectrum of reactions has been exploited: from the very lowest energies to regimes in which the projectile moves faster than 30% of the speed of light, and with short-lived rare isotopes as projectiles aimed at stable targets or with beams of stable nuclei encountering other stable or radioactive targets. Transfer reactions using the helical orbit spectrometer (HELIOS) at ATLAS and collisions creating metastable states in light dripline systems at TAMU and FSU provided new information about the structure of exotic nuclei, and fast beams of rare isotopes at NSCL reached far into the neutron-rich territory. In addition to the national user facilities and inherent to the breadth of nuclear reactions, the ARUNA laboratories made important contributions based on their unique beams, which include mono-energetic photons (HIγS) and neutrons (TUNL, Ohio, Kentucky, Massachusetts-Lowell, ND). Critically for reaction studies, TAMU, ND, FSU, and TUNL also offer magnetic spectrometers.

In concert with experiment, the theory that explains the dynamics of the collision and its relationship with the structure of the participant nuclei has also seen impressive progress. Theory achieved accurate, microscopic predictions of thermonuclear reactions that power the Sun and terrestrial fusion and obtained interactions for reactions with heavier isotopes from the same many-body framework used for structure. Reaction theories expanded more broadly to comprise a high-level of complexity in the collision dynamics. Beyond the imagination of the last Long Range Plan, a surge of Bayesian analyses and other state-of-the-art statistical tools were used to describe nuclear reactions, and seminal steps were taken toward leveraging quantum computing to simulate nuclear dynamics.

In the future, ATLAS and the ARUNA laboratories will enable low-energy reaction studies along isotopic chains rooted at and near stability, paving the path toward understanding the evolution of nuclear structure and reactions as the neutron–proton ratio increases. Among the notable opportunities are the availability of a triton beam at FSU and unique beams of fission fragments from nuCARIBU. At FRIB, reactions with the shortest-lived isotopes and up to the highest energies will probe nuclei with extreme neutron skins at the HRS; transfer reactions at the Re-Accelerator (ReA), for example using ISLA—combined with reaction theory—will enable the indirect measurement of neutron-capture processes critical for nuclear astrophysics and national security. The FRIB400 project's doubling of the energy available at FRIB would not only increase reaction rates by employing higher luminosities but also would enable new reaction mechanisms to be used.

In theory, novel approaches are expected to advance the time-dependent description of the complex fusion and fission processes; provide an increasingly broad treatment of nuclear reactions and structure on an equal footing and with microscopic interactions; and capitalize on the momentum of Bayesian analyses and uncertainty quantification, artificial intelligence/machine learning and emulations, and exascale high-performance computing as well as quantum computing capabilities.

4.7 WHAT IS THE ORIGIN OF CLUSTERING AND WHAT ROLE DOES IT PLAY IN NUCLEAR REACTIONS?

Neutron halos are an example of nuclear structures in which nucleons cluster. Although they are most prevalent in light and medium-mass systems, such clustered configurations also appear in heavy nuclei, where they play a key role in alpha decay. Clustering is also intimately connected to the production of energy in the thermonuclear fusion reactions that make the stars shine, create the biological elements of life, and fuel the recent successful net energy gain at the National Ignition Facility. Clustering is responsible for carbon-based life: the metastable carbon-12 state (known as the Hoyle state) responsible for en-

Sidebar 4.3 Clusters in Nuclear Structure, Reactions, and Astrophysics

Light nuclei with even and equal numbers of protons and neutrons often exhibit cluster substructures when the energy sits near a threshold where parts of the nucleus would separate. The building blocks of these clusters are often alpha particles, or helium-4 nuclei. In nuclei with a few extra neutrons, molecular structures can form where the extra neutrons are shared between the alpha clusters. The second 0+ state of carbon-12 is called the Hoyle state (Figure 1) and is perhaps the most well-known and consequential alpha cluster state: without it, we wouldn't exist! The Hoyle state is crucial for the nucleosynthesis of carbon-12 and oxygen-16 in helium burning stars (Figure 2). In addition to low-background measurements of these reactions, oxygen-16 formation can be studied in terrestrial experiments by performing the reaction in reverse order, where a gamma-ray photon strikes the oxygen-16 and produces an alpha particle and carbon-12 (Figure 3). Clustering also plays an important role in the formation of alpha particles in the decay of heavy nuclei. Some alpha-emitting nuclei are useful for radiation therapy because the alpha particles travel only short distances in the human body and allow for the local targeting of cancer cells.

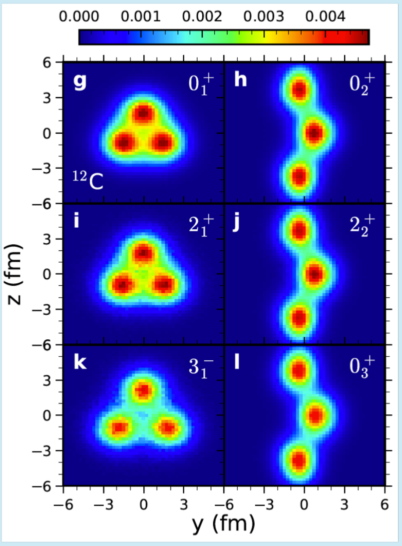


Figure 1. Various cluster structures calculated for nuclear states in the carbon-12 nucleus, using nuclear lattice effective field theory [S37].

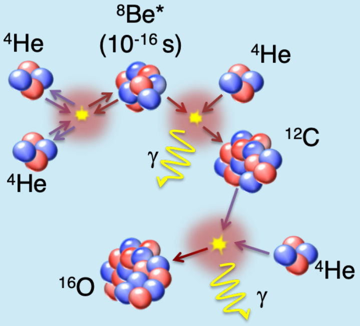


Figure 2. Schematic of the nuclear reactions involving alpha particles that power stars like the Sun. The structure of the helium-4 nucleus (alpha particle) is particularly conducive to clustering [S38].

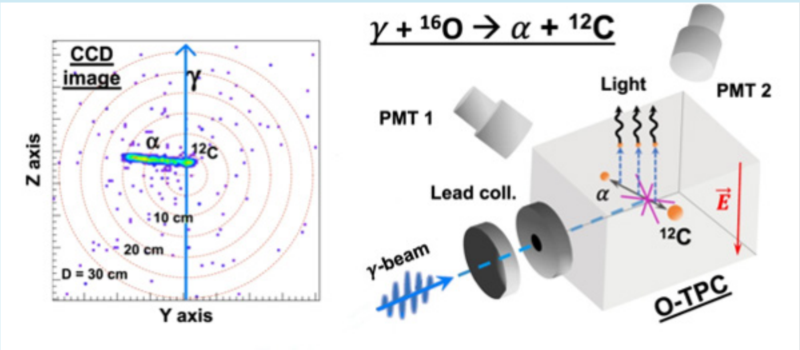


Figure 3. Demonstration of a novel measurement of the alpha capture reaction on carbon-12, using an optical time projection chamber and a gamma ray beam from the HIgS facility at TUNL. This reaction is highly influenced by resonances on alpha cluster states [S39].

hancing the production of carbon and oxygen in stars consists of three alpha particles (Sidebar 4.3).

Throughout the past 7 years, microscopic computations have begun to provide a more fundamental understanding of halo nuclei and alpha-particle clustering in lighter nuclei. Experiments at US facilities—including at ARUNA laboratories—and abroad, combined with theory have yielded new insights into the interplay between clustering and fusion rates. However, more work, especially in heavier systems, is needed to arrive at a comprehensive understanding of clustering. The super-allowed alpha-decay chain xenon-108–tellurium-104–tin-100 was observed for the first time in experiments at ATLAS. The coming decade will see many laboratories working together and in conjunction with theory to further elucidate the role of nuclear clustering in reactions and radioactive decays.

4.8 WHAT IS THE NATURE OF THE NUCLEAR FORCE?

This rich variety of nuclear phenomena emerges from the nuclear force. During the past 7 years, significant cross-fertilization of ideas and techniques has occurred between low-energy nuclear physics and other strongly interacting quantum systems, such as cold atomic gases or materials with strongly correlated electrons. Ultimately, an accurate description of the nuclear force is needed for a precise and predictive theory of nuclei. Much of the progress toward such a theory has derived from increased control of the inter-nucleon interactions that are the starting point of microscopic calculations, but significant open questions remain: their answers will be magnified in dripline systems. During the last decade, we have begun to tie the nuclear force to quantum chromodynamics (QCD) through lattice simulations of few-nucleon systems. A challenge for the forthcoming decade is to make these lattice calculations (Sidebar 3.1) accurate enough that they provide meaningful constraints and to connect them, via effective field theories, to microscopic calculations of nuclear structure and reactions, thus enabling predictions more firmly grounded in QCD.

4.9 WHERE DO THE NEXT TEN YEARS TAKE US?

By 2030, a combination of mean-field models and first-principles methods will offer predictions—with quantified uncertainties—for nuclear structure and reactions in and, in some cases, beyond medium-mass nuclei. These world-leading predictions will be weighed against a flood of new experimental data from the full suite of cutting-edge nuclear facilities that the United States has invested in; new upgrades to FRIB, ATLAS, and ARUNA laboratories; and instruments that will open new possibilities for nuclear science investigations. This research will be carried out by a highly skilled, diverse, and inclusive nuclear science workforce who will continue to lay bare the secrets of the atomic nucleus, revealing the powerful ways in which it shapes the universe and can be harnessed to improve people's lives.

5 NUCLEAR ASTROPHYSICS

Nuclear astrophysics underpins comprehensive connections across immense scales of size: from atomic nuclei to exploding stars. Nuclear processes began shaping the universe a few minutes after the Big Bang, and from the beginning of the cosmos until the present epoch, they have governed the birth, life, and death of stars and the physics of some of the most exotic matter in the universe. Nuclear astrophysics is intrinsically an interdisciplinary field, with nuclear processes at its heart.

A coherent experimental and theoretical effort in nuclear physics is required for the interpretation of observational multi-messenger signatures carried by photons, seismic waves, gravitational waves, neutrinos, and cosmic rays. The James Webb Space Telescope can see from the elemental abundances of the oldest stars in the Galactic halo to those newly formed in kilonovae. Spectroscopic studies of chemical inclusions in meteoritic and interstellar media have emerged as powerful identifiers of the origin of elements in stellar winds or stellar explosions. Gamma-ray observatories from Integral to Fermi show the highly radioactive nature of our Galaxy and highlight the continuous ongoing production and decay of short-lived nuclei. Neutrino observatories such as Borexino reveal the internal composition of the Sun. Starquakes (observed as variations in the emitted light) provide critical information about the interior of stars from the Sun to white dwarfs. Time-domain astronomy, especially the Vera Rubin Telescope, will reveal millions of nuclear-powered transients in the next decade. Next-generation gravitational wave observatories will unveil the exotic matter at the core of neutron stars and their role in galactic chemical evolution. Nuclear physics is fundamental to interpreting this rich set of observations.

The detection of the gravitational wave signal GW170817 simultaneously with electromagnetic transients identified the merging of neutron stars as a potential site for the r-process and hence an origin of heavy element production in the universe. Multi-messenger signals indicated the synthesis of the elements up to the lanthanides and beyond. The form of the gravitational wave signal gave insight to the behavior of the densest form of matter in the universe. These observations verified a decades-old predicted site for the origin of the heavy elements and firmly linked neutron matter to the universe, posing new challenges for nuclear physics.

The diversity of astrophysical phenomena demands a broad range of tools, facilities, and approaches. The experimental study of nuclear reactions that sustain stars and drive stellar explosions also requires a wide range of tools and approaches. These include small accelerators at universities and underground laboratories used to study charged-particle reactions, national and international radioactive-beam facilities used to explore nuclear processes with unstable nuclei for stellar explosions, and intense neutron sources used to explore the different neutron-capture reactions that produce the heavy elements. New experimental capabilities and methods developed at these universities and laboratories, combined with necessary advancements in theory and modeling, open new doors into our study of the universe.

As with all scientific pursuits, answering the most challenging open questions requires a diverse and well-trained workforce that is engaged at all levels—undergraduate interns, graduate students and early career scientists, and technical staff and tenured professors—and from small university groups to large international collaborations. For nuclear astrophysics, this workforce further requires broad, multidisciplinary expertise connecting nuclear physics experiment and theory with astrophysics and astronomy. Multidisciplinary centers, such as the Joint Institute for Nuclear Astrophysics, the Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS), and the Nuclear Physics from Multi-Messenger Mergers (NP3M), combining nuclear, astrophysics, astronomy and other fields have proven to be essential for providing this training.

In this Long Range Plan, we identify the **key questions for nuclear astrophysics** in the next decade and describe **the opportunities** for finding the answers. We study the nuclear physics of a broad range of stellar and transient events by examining gravitational wave, neutrino and electromagnetic signals, nucleosynthetic elemental distributions, radioactive signatures, and stardust fingerprints. This knowledge drives the development of novel instrumentation and experiments to measure the most significant nuclear processes while advancing theoretical and computational approaches toward understanding these observations and solving the key questions of the field. Observation, experiment, theory, and computation work in concert to reveal crucial aspects of the life cycle of stars.

5.1 FIRST STEPS IN CHEMICAL EVOLUTION

Before the birth of stars, the Big Bang produced the first atomic nuclei: hydrogen, helium, and a small amount of lithium. Building on these few ingredients, the first stars emerged, ending the dark ages of the universe with their light and beginning to seed the universe with heavier elements. Open questions remain, particularly the lithium problem: the disagreement between the amount of primordial lithium observed and the abundances predicted in the framework of the Big Bang. With no satisfying solution, we are left with an opportunity to explore further—do we truly understand the Big Bang, or are we neglecting an important aspect of nuclear physics in this process? In the next decade, more precise measurements of the reactions that govern the Big Bang and theoretical investigations of potentially important physics, together with refined observations, will help answer this question.

The James Webb Space Telescope opens new opportunities for direct observation of the oldest objects in the universe. The recent discovery of the oldest galaxies, now awaiting spectroscopic analysis, will shed light on the very first massive stars in the universe. These first-generation stars appear to have bridged the absence of stable nuclei with atomic mass 5 and 8 by forming alpha clusters (Sidebar 4.3). It now seems likely that the oldest stars in the universe develop deep convective stages, making them potential early sites of novel nucleosynthesis pathways, such as the i-process.

One of the fundamental challenges for nuclear astrophysics is the ability to measure nuclear reaction rates at extremely low energies near the reaction threshold. Since the last Long Range Plan, impressive progress has been made in the measurement of key reactions from these first steps of chemical evolution. Advances in facilities, instruments, and techniques have enabled measurements at extremely low energies as well as high-precision measurements at higher energies far off stability, which are critical for guiding theoretical extrapolations into the astrophysical energy regime. Improvements in the associated reaction theory, such as ab initio and sophisticated R-matrix techniques, have also reduced the uncertainties for these reaction rates. In a complementary effort, dramatic progress has been made in the past decade in 3D simulations of stellar environments, guiding a better understanding of the onset of the nucleosynthesis of heavier elements from carbon to iron; this understanding is critical to interpreting new direct observations from the James Webb Space Telescope and stellar surveys.

5.2 WHAT MAKES THE SUN SHINE?

The standard solar model, in combination with observations such as helioseismology and neutrino detection, have taught us a great deal about our nearest stellar neighbor: the Sun. However, observational discrepancies call into question the reliability of the standard solar model.

A recent major achievement was the first observation, by the Borexino experiment, of neutrinos produced in the carbon–nitrogen–oxygen (CNO) cycle in the Sun (Sidebar 5.1). The interpretation of these

Sidebar 5.1 First Observation of Neutrinos from the Sun's CNO Cycle

The discovery that neutrinos are massive particles—and that they change from one kind to another as they propagate—was in part made by nuclear physics experiments studying neutrinos from the Sun. The Sun and other stars shine because of nuclear fusion cycles in their cores. In young and middle-aged stars, fusion can happen in two ways: hydrogen fuses directly into the next-heavier element, helium (which is like the approach taken by terrestrial fusion reactors), or carbon, nitrogen, and oxygen catalyze the reaction. The rates of these processes in a star depend on how hot it is and on how many elements heavier than hydrogen are in its core. Therefore, measuring the neutrinos produced by these cycles not only tells us about the properties of the neutrinos themselves but also reveals something about the composition of the Sun's core and the creation of our own solar system. The Borexino experiment has detected carbon–nitrogen–oxygen (CNO) fuel cycle neutrinos from the Sun for the first time (Figure 1). Their observation indicates that the Sun likely contains a large mixture of these heavier elements, despite the fact that observations of the solar surface seem to show very few of them (Figure 2). The good precision of these measurements has provided a first glimpse, but more precision will be needed to determine which of the models—"few heavy elements" or "lots of heavy elements"—is correct.

observations required comparison with state-of-the-art predictions, which relied on precise measurements of nuclear reaction rates resulting from several years of work at aboveground and underground accelerator laboratories. From such comparisons, a new estimate was obtained of the abundances of various elements in the solar core. This synergistic effort is a significant step toward resolving a long-standing discrepancy between the solar composition inferred from spectroscopy of sunlight and from helioseismology.

Answering the remaining questions about the nuclear processes in the Sun will require measurements of nuclear rates at low-energy accelerators at ARUNA laboratories, including the deep underground Compact Accelerator for Performing Astrophysical Research (CASPAR). Ongoing efforts from these facilities will be essential for interpreting high-precision measurements of the neutrino flux from the CNO cycle in the Sun with the proposed neutrino detector Theia.

5.3 FROM GIANT STARS TO WHITE DWARFS

Most stars, like our Sun, cannot ignite carbon in their cores and end their lives as carbon/oxygen white dwarfs. A few stars are massive enough that the internal pressure is high enough to ignite carbon burning. They become super asymptotic giant branch stars and leave behind white dwarfs whose composition is dominated by oxygen, neon, and magnesium.

White dwarf stars are prime objects for asteroseismology because of their simple abundance structure. The uncertainties in the extracted information are primarily due to the limitations in our knowledge of the reaction rates of the triple-alpha process and subsequent alpha capture reactions that determine the ratio of carbon-12 to oxygen-16 and the distribution of these two elements within the white dwarf. Present reaction rate extrapolations disagree with the observed seismology signals, pointing to potential new discoveries.

Asymptotic giant branch stars have an additional nuclear chapter in their life story, but this one does not start in the star's core. Instead, mixing between the hydrogen and helium burning shells creates a powerful source of neutrons, produced by several helium-induced reactions on carbon-13 and neon-22. A series of neutron captures, mitigated by beta-decays, build heavier nuclei all the way to lead along the edge of stability in the slow neutron capture process (s-process). The reactions that produce these neutrons are being studied at ARUNA laboratories and at deep underground sites, and the neutron capture processes are measured at facilities such as the Los Alamos Neutron Science Center (LANSCE). New methods are under development to enable direct neutron capture studies with radioactive beams.

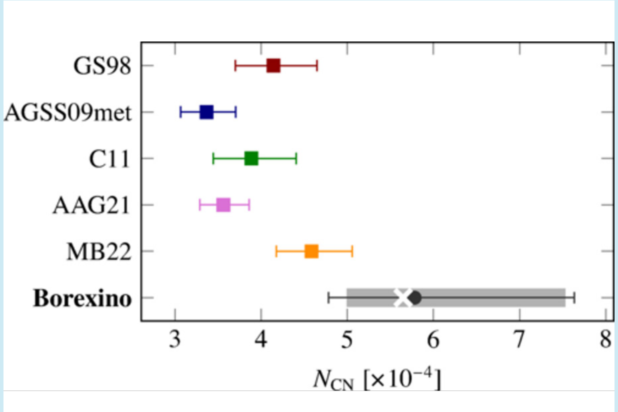


Figure 1: Relative CNO abundances from the Sun's photosphere as measured by stellar spectroscopy (colored squares) and by the Borexino neutrino measurement (black circle). The grey band represents the uncertainty due to remaining uncertainties in the underlying nuclear reaction rates [S40].

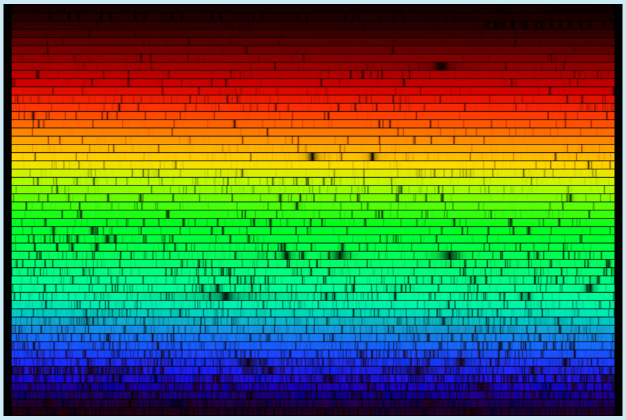


Figure 2: Visible light spectrum of the Sun. The dark absorption bands are indicative of various elements and compounds in the Sun's atmosphere [S41].

5.4 OUR EPHEMERAL SKY

The overwhelming majority of stars will end their lives as white dwarfs composed of helium; a mix of carbon and oxygen after helium burning; or, in a smaller number of cases, a mixture of oxygen, neon, and magnesium. Transfer of mass (accretion) from a binary companion onto the highly degenerate surface of a white dwarf can trigger a thermonuclear explosion: a nova, as was recently observed in RS Ophiuchi.

Depending on the white dwarf composition, nova outbursts can eject elements up to and beyond calcium into the interstellar medium. A subset of white dwarfs may eventually lead to thermonuclear supernovae explosions, observed as Type Ia supernovae, which have been used as standard candles in cosmology.

Multidimensional simulations of the simmering white dwarf atmosphere, just before thermonuclear runaway, have revealed a natural mechanism for mixing white dwarf material into the accreted envelope, solving a longstanding observational puzzle about the nature of nova ejecta. These improved models also indicate that novae may produce lithium in sufficient quantities to influence galactic chemical evolution. Critical reactions producing observables such as isotopic ratios in presolar grains have been studied in great detail using high-precision accelerator-based measurements at ARUNA laboratories, ATLAS, and the National Superconducting Cyclotron Laboratory (NSCL). With the rapidly growing knowledge of the associated reaction rates, novae are poised to become the first astrophysical site for which the nuclear-physics-driven uncertainties are fully addressed.

The fundamental puzzle for thermonuclear supernovae is the determination of the type (or types) of binary systems that host the explosion. This puzzle will be solved in the coming decade by a combination of sophisticated and multidimensional simulations along with measurements of the reactions that trigger the explosions.

Stars more massive than ten Suns meet a very different fate. Eventually, a core composed of iron develops from a chain of fusion processes. At this point, no more nuclear energy is available to the star, and it begins to collapse. The situation is exacerbated when electrons start to disappear as they are captured by nuclei, reducing the pressure. The electron capture rates that drive this process are based on theoretical predictions; charge-exchange reactions at FRIB provide unique opportunities to test and constrain these predictions.

The collapse of the core is suddenly halted when densities approach nuclear densities. The core is now a newborn neutron star, whose birth launches an outward shock wave. The power of the shock wave depends on the nuclear incompressibility, which has been probed by measurements of the breathing mode in neutron-rich nuclei. In the past decade, these and other observations, such as the maximum mass of observed neutron stars, have enabled considerable improvements in our understanding of the nuclear physics that drives core-collapse supernovae.

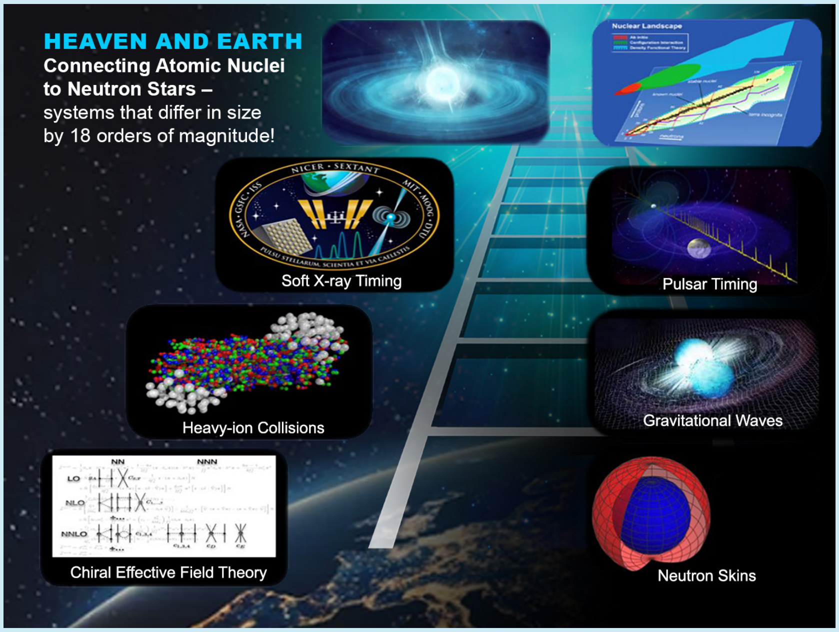
This initial shock wave eventually stalls, and the mystery, until recent years, has been how this shock wave is reenergized. Neutrinos, carrying off the binding energy of the newborn neutron star, stream out of the core with 100 times more energy than the supernova shock wave. In the past decade, multidimensional simulations incorporating spectral neutrino radiation transport and sophisticated calculations of neutrino–matter interactions have demonstrated that this neutrino-reheating mechanism is in fact the cause of the supernova explosions. The explosion and other observations, such as the typical mass fraction of the ejected nickel-56, are now reliably reproduced by state-of-the-art models. However, if the neutrino energy injection is insufficient to reenergize the shock wave, then it eventually dies out and retracts, causing the neutron star to grow in mass until it becomes a black hole. Even when a supernova occurs, the neutron star could still transition into a black hole. This possibility complicates predicting the mass distribution of black holes. In the past decade, our understanding of the nuclear physics that drives core-collapse supernovae has significantly improved, including theoretical studies of the hot nuclear equation of state (EOS) that governs the newborn neutron star.

More unusual supernova mechanisms, such as pair-instability supernovae, add a new layer of complexity. Because these events leave no remnants, any star in the mass range that leads down this road to stellar death will not produce a black hole. Consequently, models predict a gap in the possible masses of black holes. This so-called black hole mass gap depends on the energy release of oxygen fusion reactions in shell carbon burning. (Figure 5.1) Recent simulations have used experimentally constrained rates for these reactions, to better identify the range of the mass gap resulting from this one reaction rate.

The next galactic supernova promises a unique opportunity for the direct multi-messenger detection of gravitational waves, electromagnetic radiation, and neutrinos of all flavors. Interpretation will require improved understanding of nuclear matter, neutrino–matter interactions, and neutrino flavor conversion. Advances in reaction theory to improve the prediction and modeling of compound and indirect nuclear reactions provide significant future growth opportunities. The debut of FRIB enabled studies of reaction rates to reach species with even shorter half-lives. FRIB400 would significantly extend that reach to include the study of photon- and neutron-driven reaction patterns in the emerging supernova shock wave.

Sidebar 5.2 Neutron Star Inspired Density Ladder

Since neutron stars—compact objects with the mass of the Sun but with a radius of only about 10 km—were first discovered by Jocelyn Bell more than 50 years ago, they have become unique cosmic laboratories for the study of dense matter over an enormous dynamic range. As such, neutron stars provide answers to some of the most fundamental questions animating nuclear science today: What are the new states of matter that emerge at exceedingly high density and temperature? and How were the heavy elements from iron to uranium made?



[S42]

Important developments in theory, experiment, and observation in the last few years have spearheaded a unique and lasting partnership among nuclear physics, astrophysics, and gravitational-wave astronomy. None of these developments has been more influential than GW170817, the historic detection of gravitational waves from the binary merger of two neutron stars. The nuclear equation of state, which underpins the structure of neutron stars, has been greatly refined by several additional developments. Modern chiral effective field theory provides a reliable framework for our understanding of low-density neutron-rich matter. Even though a neutron star is more than 18 orders of magnitude larger than the lead-208 nucleus, Jefferson Lab's measurement of the neutron-rich skin of lead-208 has provided important constraints on the size of neutron stars. Finally, pioneering observations by NASA's NICER mission provide vital information about the exotic matter that may reside in the stellar interior.

The confluence of so many advances motivates the creation of a so-called equation of state density ladder, akin to the cosmological distance ladder. As illustrated in the Figure, no one method can determine the equation of state over its vast density domain, yet each rung on the ladder informs the equation of state in a suitable density domain that overlaps with its neighboring rungs.

To fully realize the discovery potential inherent in experiments involving rare-isotope beams and multi-messenger observations, the community must foster interdisciplinary collaborations involving theorists, experimentalists, and observers with a broad range of expertise and backgrounds. Third-generation gravitational-wave observatories, such as the Cosmic Explorer in the United States and the Einstein telescope in Europe, promise unprecedented fidelity in the detection of neutron-star mergers. At nuclear physics laboratories, the MESA facility in Germany promises increased precision in the determination of the neutron-rich skin of lead-208. Finally, a timely energy upgrade of the recently completed Facility for Rare Isotope Beams (FRIB400) offers a golden opportunity to use the collision of heavy ions to probe the equation of state in regions of critical importance for multi-messenger astronomy.

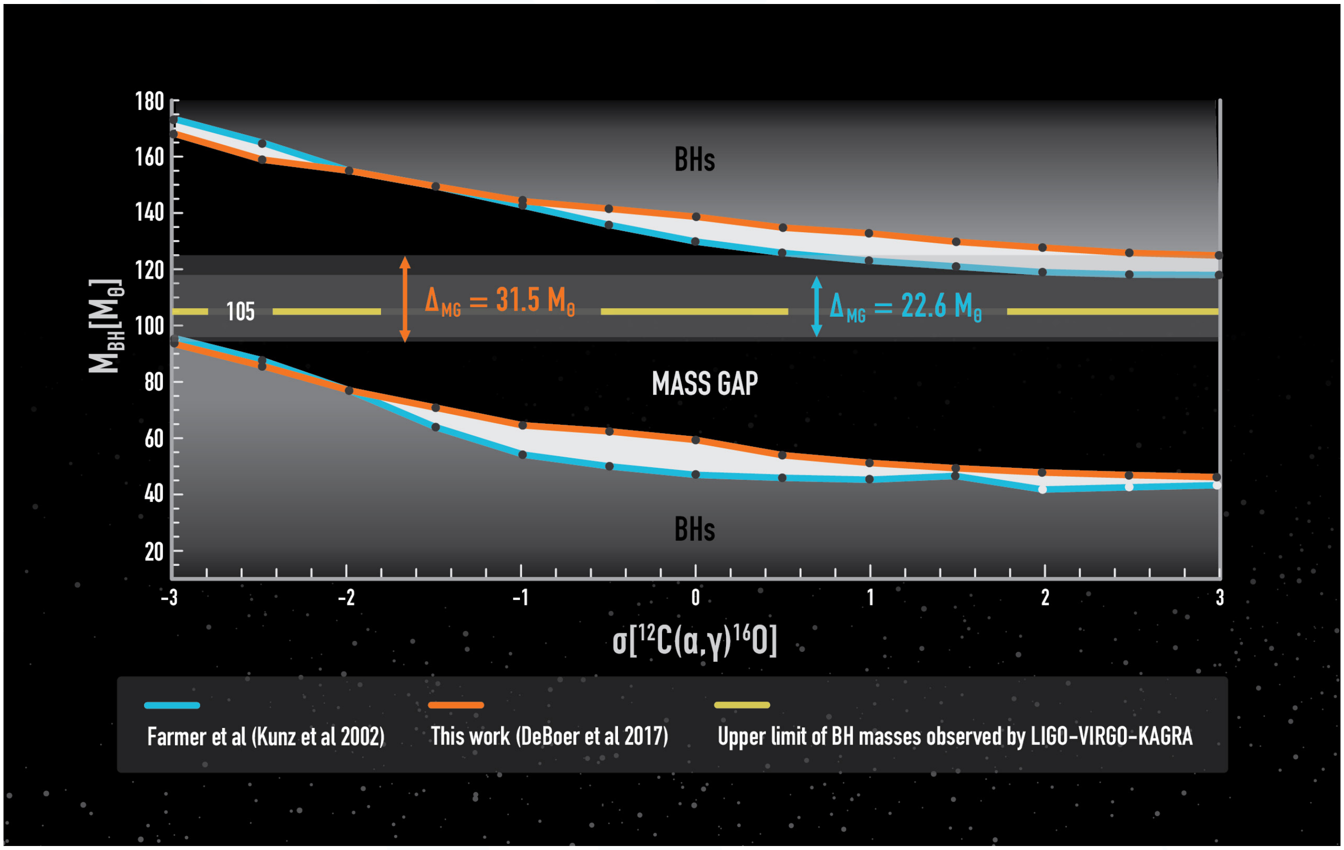


Figure 5.1. The nuclear physics of the black hole mass gap. *The width of the black hole depends critically the reactions that drive stellar helium burning, including the triple alpha process and the capture of alpha particles on carbon-12. The rate of the carbon-12 alpha capture reaction at low temperatures has been used to set new boundary conditions for the black hole mass gap (blue). A new analysis of the low-energy contributions to this reaction has reduced the experimental uncertainties, leading to a reevaluation of the mass gap boundaries (orange). The yellow line shows the maximum premerger black hole mass from the most recent LIGO–Virgo–KAGRA observing run [21].*

Ongoing experimental studies of reactions associated with the p-process as a source of the rarest isotopes in the universe are required. To properly model the n-process—which is driven by sudden neutron release via the compression of matter and is a potential candidate for the weak r-process in the supernovae—cross section measurements of the pertinent reaction rates are needed. These measurements will be obtained through efforts at the ARUNA facilities, FRIB, and the upgraded Californium Rare Ion Breeder Upgrade (nuCARIBU) at ATLAS.

Quantitative matching of elemental abundances to astronomical observations will require extended simulations, reaching beyond the initial seconds when the explosion is powered and the nuclei are made to the hours, days, and months later when these newly formed elements are observed by telescopes. Only then will we know whether our simulations match reality and whether we truly understand the various ways these different kinds of stars end their lives.

5.5 EXOTIC ASTROPHYSICAL LABORATORIES: NEUTRON STARS AND THE HEAVY ELEMENTS

Neutron stars are unique cosmic laboratories for the study of dense matter throughout an enormous dynamical range. They are also a possible production site for the heaviest elements. As such, they answer some of the most fundamental questions animating nuclear science today. Observations of massive neutron stars combined with the simultaneous determination of the mass and radius of two neutron stars by the Neutron star Interior Composition Explorer (NICER) mission informs the EOS at the highest densities found in the neutron star core. Recent and future neutron skin measurements, in particular by the Lead (Pb) Radius Experiment (PREX) at Jefferson Lab and the Mainz Radius Experiment (MREX) at the Mainz Energy Recovery Superconducting Accelerator (MESA), add to our understanding of the EOS. The confluence of so many significant advances motivate the creation of a so-called EOS density ladder like the distance ladder used in cosmology (Sidebar 5.2).

Neutron stars can accrete material from companion stars, driving astronomical transients. For example, x-ray bursts (XRBs) occur on the surface of accreting neutron stars. The explosion is driven by the rapid proton capture, or the rp-process, a sequence of fast proton-capture reactions limited only by the proton drip line. Several measurements have defined the ignition mechanism, but additional studies are needed to map the reaction path and confirm the endpoint of this process, which within seconds converts the abundance distribution at the surface of the neutron star. More than 100 XRBs have been observed, many bursting on hour or even minute timescales. The high frequency of XRB observations offers a unique portal to probe neutron star properties and forge a direct link between astronomical observations and the underlying nuclear physics. A topic that is just starting to receive attention is the effect of long-lived, excited nuclear states, known as isomers, on the nucleosynthesis pathways in XRBs. Recent experiments at ATLAS and NSCL have identified and characterized critical rp-process waiting-point nuclei and tied nuclear physics to the duration of an XRB by using benchmarked 1D models. This information has enabled using XRB light curves of specific systems to extract neutron star properties. Observational evidence suggests that the ignition of the burning front begins locally and spreads across the surface of the neutron star. Recent multidimensional simulations have begun to examine the details of the burning front propagation and thermal transport across the neutron star surface, allowing us to "see" the fate of the rp-process ashes in the deeper neutron star layers.

New computing resources enable larger regions of the neutron star surface to be modeled in 3D with moderate-sized nuclear reaction networks included. More accurate predictions of rp-process nucleosynthesis and the physics of the flame propagation will require conducting multidimensional simulations to connect to astronomical observations and to understand the burst ashes and underlying nuclear EOS. The largest remaining experimental challenges for XRBs are in constraining the charged-particle reaction rates that affect the light curves and explosive nucleosynthesis of XRBs. Crucial to addressing the remaining nuclear physics uncertainties of the rp-process are improvements in the intensity of rare-isotope beams using the In-Flight Radioactive Ion Separator (RAISOR) at ATLAS and the re-accelerator (ReA) at FRIB, more sensitive and higher-efficiency detectors and new techniques, and indirect techniques combining transfer reactions with advances in the consistent treatment of reaction and structure theory to study these nuclei and constrain the reactions of interest.

A different type of nuclear-powered transient in the x-ray sky are quiescent accreting neutron stars, which have particularly long periods during which accretion turns off and the cooling of the neutron star crust can be observed over timescales of years. These systems have become unique probes of novel phases of dense nuclear matter, such as a superfluid made of only neutrons, "nuclear pasta," and even a quark matter phase transition in the neutron star core. Experiments have begun to address some of the nuclear physics of neutron-rich nuclei that drives quiescent neutron stars, from stability to beyond the neutron dripline. Nuclear masses directly affect nuclear heating and cooling via Urca processes, and measurements are being extended to relevant neutron-rich nuclei using TOF and Penning trap techniques. Measurements of beta-delayed gamma rays and neutrons have constrained ground-state-to-ground-state transition strengths, a key pathway for nuclear transformations in accreted crusts.

The most dramatic astronomical event since the last Long Range Plan was the detection of gravitational waves from the merger of two neutron stars, GW170817. These observations showed nucleosynthesis at work and informed the nuclear EOS by determining neutron stars' susceptibility to tidal deformation by a close companion. Because of this event, the next decade has been heralded as the golden age of observations. A unique opportunity exists to determine the nuclear EOS more precisely by using third-generation gravitational wave detector concepts such as the Cosmic Explorer. These events will also provide better understanding of the origin of the heavy elements via the coincident observations of the electromagnetic transients associated with these gravitational wave signals.

5.6 THE R-PROCESS

Electromagnetic observations that followed GW170817 confirmed the long-held belief that short gamma-ray bursts are associated with binary star mergers. Observations of the kilonova—the optical afterglow—from this event provided the first direct evidence of a site for the r-process, opening a pathway to directly address one of the most important open questions in all of physics: the origin of the heavy elements.

The ability to accurately model the GW170817 kilonova remnant powered by the radioactive decay of r-process elements was a triumph for all of physics delivered by nuclear science and has ushered in a brand-new era of multi-messenger astronomy. Mass measurements and decay properties of very-neutron-rich nuclei have begun to be benchmarked against these kilonova observations and set the stage for future measurements with FRIB400 and the ATLAS *N* = 126 factory near the r-process path (Sidebar 5.3). Further decay studies will require critical tools such as the Gamma-Ray Energy Tracking Array (GRETA) and the FRIB Decay Station. Previously unknown long-lived isomers can affect the kilonova time-dependent light curve; experimental and theoretical nuclear structure input is needed to fully constrain the details of this effect. The successful development of direct techniques at the Los Alamos Neutron Science Center (LANSCE) to benchmark neutron capture reactions near stability, complemented by indirect methods and the associated reaction theory, adds to the arsenal of nuclear physics tools that can address the open questions of r-process nucleosynthesis. Future indirect measurements will benefit from a separator such as ISLA for the upgraded ReA12 reaccelerator to uniquely identify the reactions of interest. On the theory side, microscopic and mean-field approaches are helping constrain the role of fission in r-process observations: so-called fission recycling turns out to be key to what the r-process produces.

Although confirmation of the site(s) of the r-process remains a compelling open science question, major improvements since the last Long Range Plan in nuclear data, including mass measurements, astrophysical simulations, and astronomical observations, have identified additional scenarios that contribute to the origin of elements above iron. New nucleosynthesis processes are being discovered and explored, for example the i-process in early stars, the n- and vp-processes in core-collapse supernovae, and a weak r-process in neutrino-driven winds. Laboratory measurements of the critical nuclei and reactions in

Sidebar 5.3 Element Production in a Neutron Star Merger

Understanding the synthesis of the heavy elements, primarily those with atomic numbers greater than 26 (iron), remains one of the biggest open questions in nuclear astrophysics. Thanks to the first-of-its-kind detection of the optical counterpart to a gravitational wave event, we now know that neutron star mergers can form some of the heavy elements we see around us. Analysis of the kilonova and gamma-ray burst associated with the GW170817 gravitational wave detection has provided the first direct evidence that the rapid neutron-capture process (r-process) occurs in neutron star mergers.

The ability to accurately model the r-process-powered light curve of this kilonova was a triumph for the field and has triggered unprecedented progress in compu-

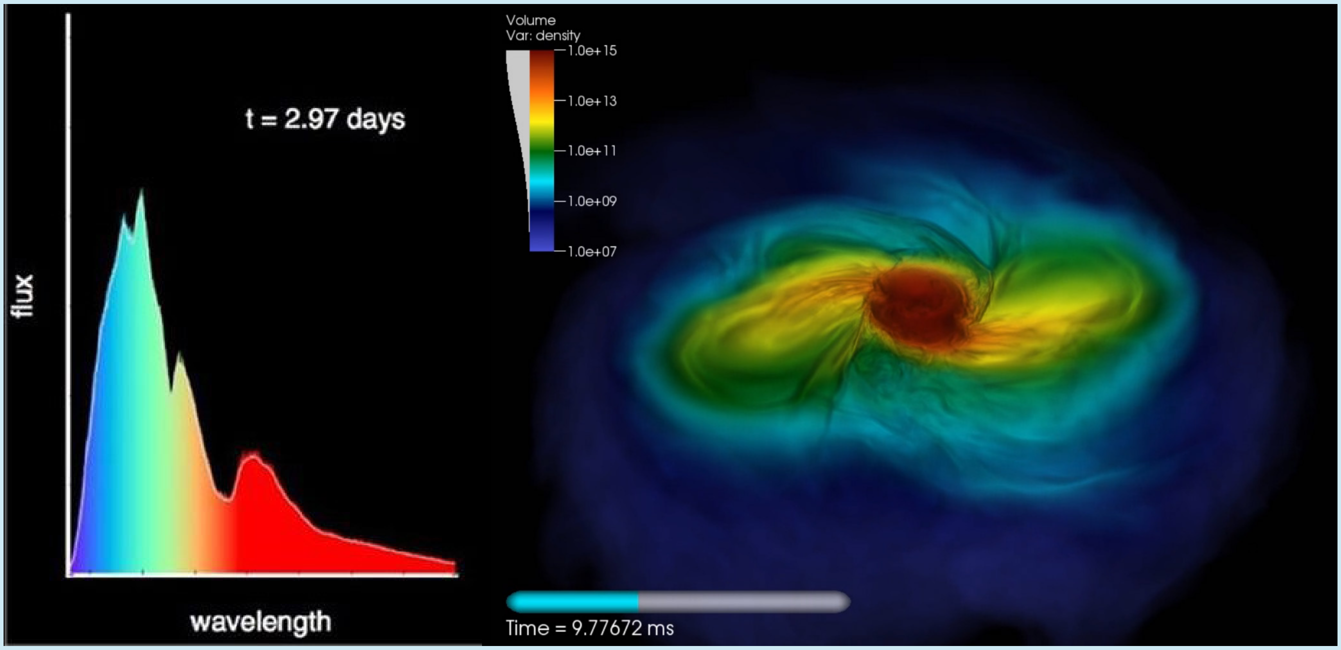


Figure 1: Detailed modeling of neutron star mergers allowed accurate interpretation of the GW170817 multimessenger sig-nals and correlated them with the underlying nuclear physics. On the left, a theoretical calculation of the evolution of the spectrum of light from a kilonova such as that associated with gravitational wave signal GW170817. On the right, modeled outflows from a neutron star merger, just after the two objects have merged [S43].

the various reaction networks for these processes are only just beginning and promise enticing results during the period of this Long Range Plan.

5.7 CONNECTIONS

Nuclear astrophysics has broader ramifications for other subfields in which the understanding of nuclear processes both drives progress and benefits from it. An example is the connection with the physics of ultrahigh-energy cosmic rays (UHECR). One important question is the nuclear composition of these very energetic particles, which holds the key to their physical origin. A heavy composition might indicate an origin in heavy-element factories like core-collapse supernovae and binary mergers. Establishing the UHECR composition at the source requires modeling ion propagation across the universe as well as in the Earth's atmosphere. Such modeling requires precise inputs on reactions like ion–photon and ion–hadron scattering from accelerators.

Another example is the connection between neutrino emissions in core-collapse supernovae and particle physics. It is important to precisely predict the features of the emitted neutrinos (near the collapsed core, where neutrinos decouple from matter), and especially their energy spectra, to use future supernova neutrino data to perform tests of neutrino physics, including flavor conversion in dense media and the possible coupling of neutrinos to particles and forces beyond the Standard Model (e.g., sterile neutrinos, Majorons, light scalars). Neutrino spectra require simulating the complex interplay of many nuclear processes using precise nuclear rates.

tational modeling of these events (Figure 1). An opportunity now exists to combine gravitational wave–triggered kilonova observations with new rare-isotope physics from experiment and theory, new equation-of-state physics, new neutrino physics, high-fidelity end-to-end computer models, and stellar spectroscopy data to quantify the contribution of neutron star mergers to the galactic heavy-element abundances for the first time. Complementary information from a range of multi-messenger sources, including galactic chemical evolution models, observations of metal-poor stars, and isotopic analysis of deep-sea sediments, have further focused our understanding of r-process elements and where they originate.

Recent efforts capitalizing on new techniques for measuring nuclear physics properties of r-process nuclei—such as precision mass measurements with Argonne's CARIBU facility (Figure 2)—have started to meaningfully constrain the nature of the environment inside a neutron star merger. Reverse engineering techniques have been used to predict nuclear masses from merger conditions with stunning accuracy (Figure 3), and to predict the nucleosynthesis patterns of mergers based on their optical counterpart, such as the one observed with GW170817. The question remains whether GW170817 was a typical merger, or if the coming decade of observational data will surprise us.

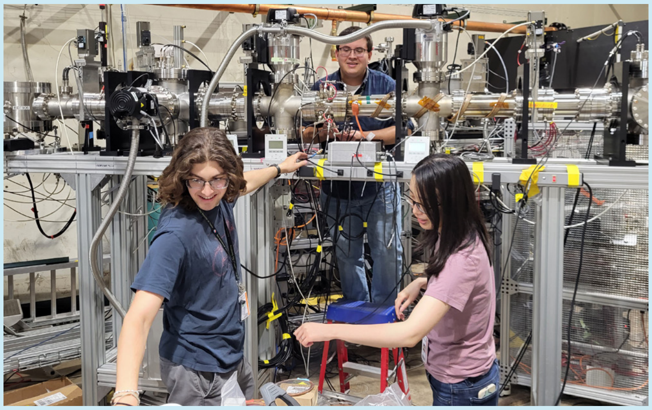


Figure 2: Early career researchers (from left to right) Caleb Quick, Adrian Valverde, and Biying Liu work on equipment such as the Canadian Penning Trap at Argonne National Laboratory to constrain the nuclear physics needed to fully understand the production of heavy elements in neutron star mergers [S44].

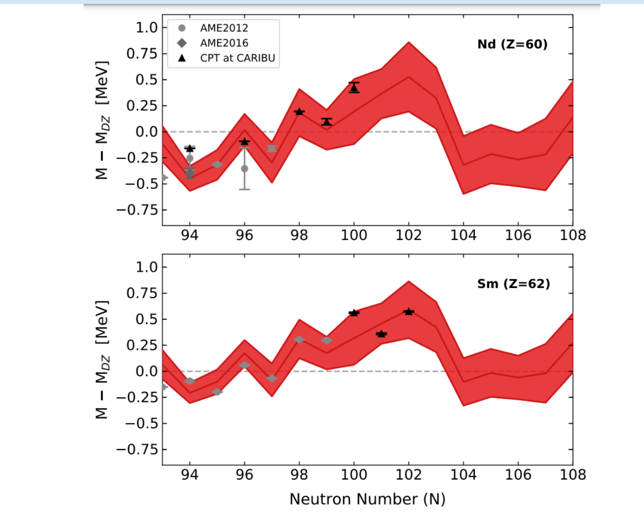


Figure 3: Researchers modeling the conditions of a neutron star merger used this information to reverse engineer the nucle-ar mass values needed to reproduce the observed element abun-dances from known r-process-enriched stars (red bands). Over-laid for two isotopic chains are the measured masses (grey and black points), demonstrating that the nuclear physics is con-sistent with a hot r-process merger [S45].

5.8 MAJOR OPPORTUNITIES

A confluence of breakthroughs in multi-messenger astronomy, laboratory nuclear physics, and computational modeling has propelled nuclear astrophysics to the forefront of science. The present multi-messenger astronomy era will provide a wealth of new observational data and will continue advancing nuclear astrophysics. As discussed throughout the chapter, major opportunities include the following:

- Measurements of stellar reaction rates, such as those critical to neutrino signatures from the Sun, to black hole mass distributions, and to the isotopic signatures of the oldest stars, and advancements in the nuclear reaction theory and stellar modeling necessary to connect those measurements to observation.
- The accurate interpretation of transients observed in upcoming all-sky surveys via the study of properties of exotic proton- and neutron-rich nuclei, modeling of the effects of nuclei on neutron star crusts and stellar remnants, and a coherent treatment of nuclear structure and reaction theory.
- Constraint of crucial aspects of the nuclear EOS through a combination of laboratory measurements of dense neutron matter, observations of neutron stars, and new comprehensive models.
- Exploring the nucleosynthesis of heavy and even superheavy elements and the corresponding effect on multi-messenger observables and galactic chemical evolution, with a combination of new rare-isotope beams and experimental techniques, improved theoretical predictions of the properties of the most neutron-rich nuclei, and incorporation of complex nuclear and astrophysical processes into high-fidelity models.

A common thread in harnessing these exciting opportunities in experimental, theoretical, and computational nuclear astrophysics in the coming decade is the need to leverage the capabilities of a very broad range of national facilities (FRIB, ATLAS) and university-based and deep underground laboratories (ARUNA), and the unique tools available at each. This collaborative effort will provide a powerful suite of experimental facilities to answer the broad range of open scientific questions. New levels of computational capabilities will be important for implementing and interpreting the measured and observed phenomena, including exascale computing, novel advances in machine learning algorithms, and emulators that reproduce the behavior of high-fidelity models at a fraction of the computational cost. The development of self-consistent, predictive nuclear structure and reaction theories across the nuclear chart will benefit nuclear astrophysics and the broader field. Moreover, to fully realize the discovery potential inherent in experiments involving rare-isotope beams and multi-messenger observations, the community must foster **interdisciplinary collaborations involving theorists, experimentalists, and observers** with a broad range of expertise and backgrounds. The need for a comprehensive range of complementary and connecting approaches, facilities, and expertise is an intrinsic feature of this field and is driven by the breadth and complex interplay of the nuclear physics needed for astrophysics.

6

FUNDAMENTAL SYMMETRIES, NEUTRONS, AND NEUTRINOS

6.1 INTRODUCTION

Research in fundamental symmetries, neutrons, and neutrinos (FSNN) encompasses a portfolio of precision measurement techniques and searches for rare processes to unlock a deeper understanding of our universe. This deeper understanding is often referred to as the search for new physics or beyond the Standard Model (BSM) physics because some features of the observed universe cannot be explained by the Standard Model. Uniquely, the FSNN community uses nuclei, the constituents of nuclei (neutrons), and low-energy neutrinos produced by nuclear processes to test fundamental symmetries and search for new particles to discover this BSM physics.

Examples of symmetry exist all around us in the natural world, from the petals on a flower to the twice-daily tides. Small deviations from these symmetries often have reasons that point to a better understanding of the natural world. In physics, we can quantify this understanding by defining a symmetry as a transformation that leaves the physical system unchanged. As discovered by Emmy Noether more than a century ago, certain symmetries of our theories imply conservation laws. These laws include the conservation of basic quantities, including energy, momentum, and electric charge, as well as more abstract quantities such as the total number of particles minus antiparticles. Therefore, by testing our understanding of symmetries or conservation laws, we can uncover new physics.

Discoveries of symmetry violations have been critical in shaping our current understanding of the universe. Everything we know relies on a mysterious concurrence of symmetry violations in the early universe that produced more matter than antimatter. For this reason, the study of fundamental symmetries and the corresponding search for new particles provides great potential for discovery. New particles may evade detection for two reasons (Figure 6.1): they may be too massive to be created in current colliders or they may rarely interact with matter, leaving no trace in our detectors. FSNN research will push the envelope of discovery with new experimental technologies. Its portfolio includes the high-priority search for neutrinoless double beta decay and a comprehensive set of precision measurements and searches for new particles to maximize this discovery potential.

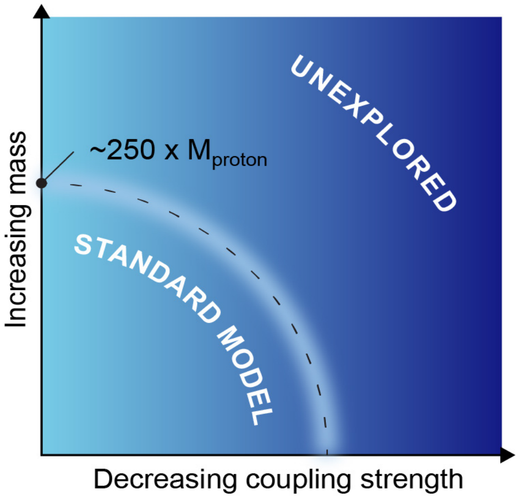


Figure 6.1. Physics beyond the Standard Model must reside at heavy masses and/or weak coupling strength. *Physicists probe such regions through searches for rare and forbidden processes, high precision measurements of allowed processes, and exploration of properties of known and hypothetical particles [22].*

The portfolio can be divided into three broad categories, as outlined in the following subsections, and tied together by critical overarching theoretical studies.

6.1.1. Searches for processes that are rare or forbidden in the Standard Model

Some processes break approximate or exact symmetries and conservation laws. Prominent examples, connected to the origin of the matter–antimatter asymmetry, are the searches for neutrinoless double beta decay and permanent electric dipole moments (EDMs) of the neutron, atoms, and molecules. Observation of neutrinoless double beta decay would prove that neutrinos are their own antiparticles and would provide the first evidence of a process that produces more matter than antimatter. Observation of permanent EDMs would signal an intrinsic arrow of time, something that has never been observed in a single particle system, thus implying time-reversal symmetry violation. Observations to date hold that the combined symmetries of charge, parity, and time-reversal must be conserved, so nonzero permanent EDMs also require violation of charge–parity symmetry, a mirror-like symmetry (Figure 6.2) that interchanges matter and antimatter.

Sidebar 6.1 The International Effort to Observe Neutrinoless Double Beta Decay

The search for neutrinoless double beta decay is a truly international effort. A strong and diverse group of physicists from around the world have rallied around the three efforts—CUPID, LEGEND-1000, and nEXO—described in the main text. This committed consortium of international partners is a necessary feature of the program given the scale of the resources required to execute it.

The three efforts are all led by distinctly international collaborations with large US components. For example, the LEGEND collaboration is almost evenly split between North America and Europe, with over 250 members from more than 50 research institutions in 14 countries. CUPID is an international collaboration led by Italy, the US, and France. The nEXO experiment is a predominantly North American collaboration with 200 scientists from 34 institutions in 9 countries.

The extremely low-background environment required for these experiments can only be achieved at a deep-underground site, which shields against cosmic rays. The host sites – SNOLAB in Canada and the Laboratori Nazionali del Gran Sasso (LNGS) in Italy – are both outside of the United States (Figure 1).

DOE is leading the formation of a consortium of international stakeholders in Canada, France, Germany, Italy, the United Kingdom, and the United States. In a forum held in April 2023 in SNOLAB, a consensus has emerged that the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one ton-scale experiment implemented in the next decade. The plan is to create an international virtual laboratory that would then coordinate the efficient and cost-effective deployment of CUPID, LEGEND-1000, and nEXO, with ton-scale experiments at LNGS and SNOLAB.

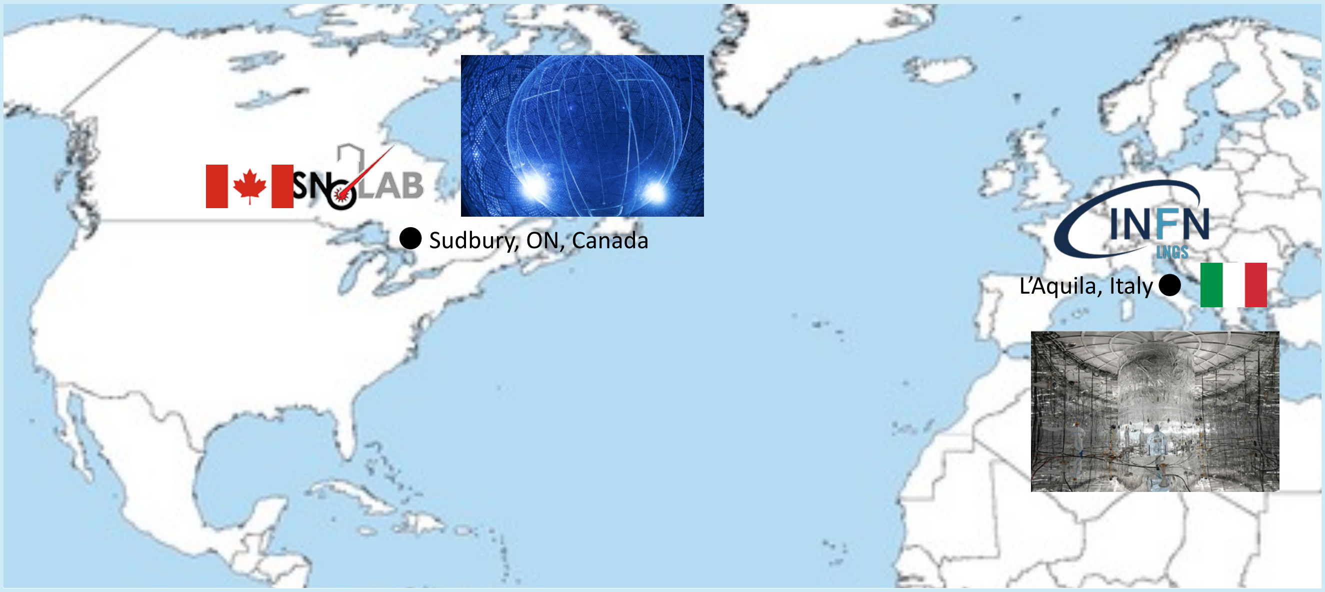


Figure 1: The search for neutrinoless double beta decay is a global endeavor. Photos courtesy of SNOLAB and INFN, respectively [S46].

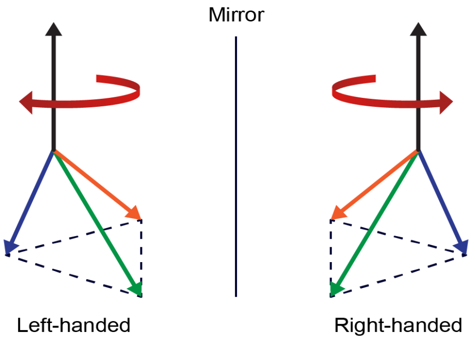


Figure 6.2. To illustrate some of the symmetries discussed in the text, consider a tetrahedron, which shows how an object and its mirror image can be distinct. *We can also use this as a stand-in for a beta decay process, which has a three-body final state. For a parent of fixed spin (large black arrow), just one "handedness" is picked, owing to the special nature of the neutrino. In other processes, the breaking of parity symmetry can be very small [23].*

Because of quantum mechanical fluctuations allowed by Heisenberg's uncertainty principle, these experiments are sensitive to mass scales well above the reach of high-energy colliders. A discovery in any of these searches would be paradigm-shifting.

6.1.2. High-precision measurements of processes allowed in the Standard Model

Processes allowed in the Standard Model include the beta decay of mesons, neutrons, and nuclei; electrons scattering on nucleons, nuclei, and electrons; and the magnetic properties of the muon. By observing quantum fluctuations and other radiative effects, measurements of these processes probe the existence of very heavy new particles—which have masses well beyond the reach of existing high-energy colliders—and light, weakly interacting particles. Precision measurements become powerful discovery tools when confronted with precise theoretical predictions.

6.1.3. Exploration of the properties of known and hypothetical light, weakly interacting particles

The chief example in the class of known and hypothetical light, weakly interacting particles are the neutrinos produced by nuclear interactions and decays. Neutrinos are electrically neutral and extremely weakly interacting particles, so they are very difficult to study, but they can also be effective messengers of the processes that power the Sun and drive supernova explosions. However, basic properties—including their masses and interaction strengths—remain uncertain. These experiments are critical for cementing our understanding of the neutrino and providing techniques that allow us to search for other light, weakly interacting particles predicted by BSM physics.

In summary, this portfolio of experiments and the theory required to interpret them are at the forefront of the quest for new physics. Great discoveries have been made, including the 2015 Nobel prize–winning discovery of neutrino oscillations using neutrinos produced in the Sun's nuclear reactions. In the next decade, this portfolio is poised for many great discoveries that tackle some of the universe's greatest questions while advancing the technologies and facilities that push the boundaries of what is measurable.

6.2 QUESTIONS, FACILITIES, AND TECHNOLOGIES

A suite of sensitive experiments and theoretical investigations enables FSNN to shed light on some of the most profound questions in science:

- What is the origin of the matter–antimatter imbalance in the universe?
- Are neutrinos their own antiparticles, and how do they acquire mass?
- Are there more forces than the four we know about?
- Are there undiscovered light, weakly interacting particles?

Although the Standard Model of particles and forces in nature is extremely good at describing the universe we see, it provides no answers to these questions. Only through experiments and related theory can we hope to address them and discover the BSM physics that can help answer them. Figure 6.3 illustrates these questions and the corresponding experimental programs that address and connects them.

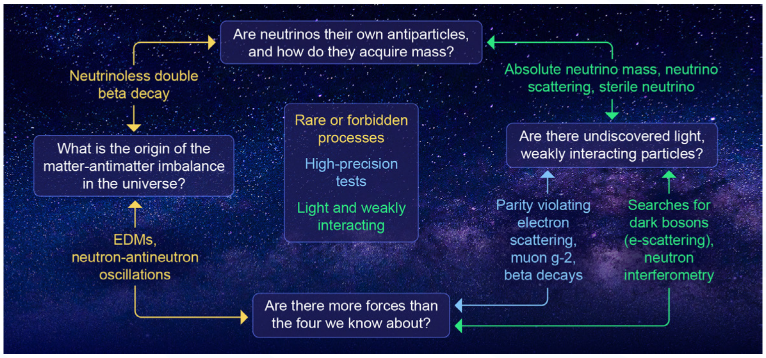


Figure 6.3. The scientific questions addressed by FSNN and the experimental programs that connect them [24].

There is a great opportunity in the coming years to address these questions. At present, the highest priority effort is the search for the Standard-Model–forbidden process of neutrinoless double beta decay, which violates lepton number—the number of leptons (neutrinos, electrons, muons, taus) in the reaction—by two units. It also requires that neutrinos are their own antiparticles. Observation of neutrinoless double beta decay is the only feasible way to test this property of neutrinos. If it is observed, then neutrinos will be implicated as key players in the creation of the matter–antimatter asymmetry in the early universe. The community has executed a suite of demonstrator-scale experiments that have proven multiple technologies. Three experiments based on these technologies are ready to search for neutrinoless double beta decay with unprecedented sensitivity. These so-called ton-scale experiments will be sensitive to decay half-lives from 10^{27} to 10^{28} years, probing a broad array of mechanisms of lepton number violation and neutrino mass generation.

Given this critical opportunity, recommendation 2 of the nuclear science community states:

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

Prospects for uncovering charge–parity symmetry violation in the coming decade are similarly auspicious. Certain breakdowns of charge–parity symmetry will lead to permanent EDMs of particles, atoms, and molecules. Experimental control techniques once limited to atoms are now extended to polar molecules in which sensitivity to charge–parity symmetry violating effects can be amplified by 3–4 orders of magnitude. Similar order-of-magnitude sensitivity enhancements also occur in deformed pear-shaped nuclei that could become available at FRIB. Permanent EDM searches in the next decade (e.g., the world's most ambitious search for a permanent neutron EDM, at Oak Ridge National Laboratory's Spallation Neutron Source [SNS]) will probe new BSM physics at scales up to a million times the mass of the proton, far beyond what can be directly probed at current or planned colliders. Moreover, new probes of charge–parity symmetry violation emerge from symmetry tests in neutron transmission.

A suite of small and mid-scale experiments will probe BSM physics in various ways, notably via precision measurements. Neutron and nuclear decays will test the quark–lepton universality of the weak interactions in the Standard Model—the strength of the weak force among quarks of different types adds up to the strength of the weak force felt by leptons. In a similar vein, rare-pion decays into electrons and muons will test lepton universality, which requires the weak force to be the same for all leptons. Experiments using parity-violating electron scattering will measure with unprecedented precision at low energies the strength of the so-called weak mixing angle, which is fundamental to the unified description of weak and electromagnetic forces.

Emerging techniques in experimental neutrino physics will continue their R&D efforts and expect to be capable of world-leading measurements in the next decade. A new technique to directly measure neutrino mass promises to reach mass scales more than a factor of 10 smaller than the ones currently probed. Quantum sensors will be applied to searches for hypothetical sterile neutrinos (i.e., neutrinos that do not participate in Standard Model interactions) emitted in beta decays. Coherent elastic neutrino–nucleus scattering, observed for the first time since the last Long Range Plan, will probe BSM interactions in neutrino–nucleus interactions. R&D will continue toward the study of neutron processes that violate baryon number—the number of baryons in a reaction. The most familiar baryons are the proton and neutron.

This program pushes the bounds of what is measurable by harnessing cutting-edge technology from large-scale cryogenics to novel quantum sensing techniques. It also drives the need for unique facilities located across the country. The combination of people, technology, and facilities are critical for making these great discoveries, and the FSNN community is well positioned to address these great questions in the next decade.

6.3 NEUTRINOLESS DOUBLE BETA DECAY

In double beta decay, two neutrons inside a nucleus simultaneously convert into two protons. The conservation of charge, energy, and lepton number require that these conversions are accompanied by two electrons and two antineutrinos. Double beta decay has a significant chance to be observed only when ordinary single beta decay is not energetically allowed. This process is possible for a few dozen nuclei. The associated half-lives for this very rare process are roughly 10^{20}–10^{24} years, much longer than the age of the universe. The double beta decay of fourteen nuclei has been experimentally observed. Neutrinoless double beta decay is a potential nuclear process in which two neutrons inside a single nucleus convert into two protons and two electrons, *but no neutrinos are emitted*. This process conserves baryon number but violates lepton number by two units. The observation of neutrinoless double beta decay would unambiguously indicate that lepton number is not a conserved quantity and that matter can indeed be created or destroyed. This result would have profound consequences for our understanding of how the universe contains so much more matter than antimatter.

Currently, no experimental evidence indicates that neutrinoless double beta decay occurs in nature. However, the existence of neutrinoless double beta decay is intimately related to one of the most important questions in fundamental physics today: what is the physics responsible for the tiny but nonzero neutrino masses? We do not know the answer, but several potential mechanisms exist for neutrino masses. These mechanisms fall into two very broad categories that make different predictions for another key question: are neutrinos Majorana fermions (i.e., are neutrinos their own antiparticles)? The existence of fundamental Majorana fermions has never been demonstrated. If the neutrino is a Majorana fermion, then the exact conservation of lepton number is not allowed because the neutrino and the antineutrino—which are one and the same—cannot have opposite lepton numbers. Hence, if neutrinos are Majorana fermions, then neutrinoless double beta decay can occur, and if it is ever observed, then neutrinos must be Majorana fermions.

Quantitatively, the connection between neutrino masses and the rate for neutrinoless double beta decay depends on the details of the BSM physics that determines neutrino masses. However, if light Majorana neutrino exchange is the dominant contribution to neutrinoless double beta decay, then the rate for neutrinoless double beta decay is directly connected to a combination of light neutrino

Sidebar 6.2 Radioisotope Harvesting at FRIB for Fundamental Physics

The Facility for Rare Isotope Beams (FRIB) will yield the discovery of new, exotic isotopes and the measurement of reaction rates for nuclear astrophysics, and will produce radioactive isotopes that can be used for a broad range of applications, including medicine, biology, and fundamental physics.

Converting waste to wealth

Radioisotopes at FRIB are produced via fragmentation when accelerated ion beams interact with a thin target. Several isotopes, including those previously unobserved, across the entire periodic table will be produced in practical quantities for the first time in the water beam dump at the FRIB accelerator. The Isotope Harvesting Project provides a new opportunity to collect these isotopes, greatly enhancing their yield and real-time availability to enable a broad spectrum of research across multiple scientific disciplines. Isotopes will be extracted from the beam dump and chemically purified using radiochemistry techniques in a process called harvesting. Harvesting operates commensally, therefore providing additional opportunities for science.

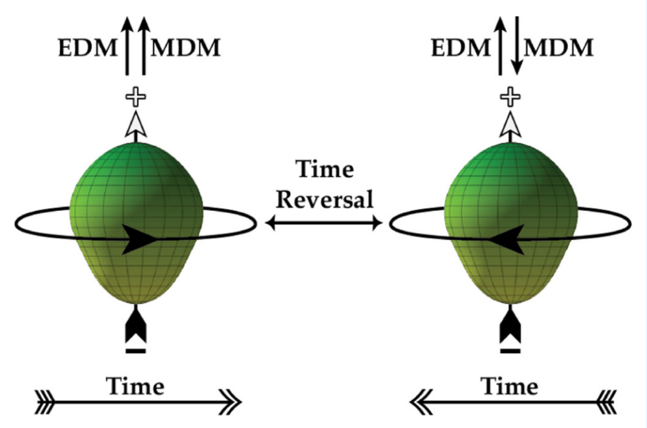


Figure 1. A pear-shaped nucleus spins counterclockwise or clockwise, depending on the direction of time [S47].

Pear-shaped nuclei enable new-physics searches

With uranium-238 ion beams, these methods can produce heavy, pear-shaped nuclei that can be used to search for violations of fundamental symmetries that would signal new forces in nature. For example, a nonzero permanent electric dipole moment (EDM) would break parity and time-reversal symmetries. Figure 1 shows a pear-shaped nucleus spinning under applied electric and magnetic fields. Its magnetic dipole moment (MDM) is nonzero, and if its EDM is also nonzero, then its spin-precession rate changes if the direction of time is reversed. Heavy, pear-shaped nuclei can greatly amplify the sensitivity to a nonzero EDM and complement neutron EDM studies. Pear-shaped isotopes such as radium-225 and protactinium-229 will be produced in abundance at FRIB, and their EDM effects can be further enhanced by using them to form polar molecules, which can then be probed using cutting-edge laser techniques. The unique sensitivity of these experiments opens otherwise inaccessible windows on new physics.

masses, called $m_{\beta\beta}$, which can be used to quantify the discovery potential and significance of neutrinoless double beta decay experiments. The quantity $m_{\beta\beta}$ can be expressed in terms of quantities that are measured in neutrino oscillation experiments and a few unknowns, such as the overall scale of neutrino masses and two possible orderings of the neutrino spectrum, conventionally called *normal* and inverted ordering. Our current knowledge of neutrino mass and nuclear theory indicates that ton-scale neutrinoless double beta decay experiments are poised to influence our understanding of neutrinos in a potentially decisive way by entirely covering the inverted ordering scenario for $m_{\beta\beta}$, as well as the normal ordering if the mass of the lightest neutrinos is greater than 50 meV. Conversely, a measurement of the rate for neutrinoless double beta decay can be converted into an independent measurement of neutrino masses. The combination of data from neutrino oscillation experiments, the large-scale structure of the universe, precision measurements of beta decay and neutrinoless double beta decay is required to help us piece together the neutrino mass puzzle and reveal the BSM physics that lies beneath. Although the physics reach of neutrinoless double beta decay experiments is usually framed in terms of the effective mass $m_{\beta\beta}$, it is important to keep in mind that $m_{\beta\beta}$ covers only part of the large discovery potential associated with mechanisms of neutrino mass generation and lepton number violation.

The interpretation of neutrinoless double beta decay experiments and the identification of the mechanism

Sidebar 6.3 The Effects of Ionizing Radiation on Superconducting Qubits

The use of quantum sensors and quantum computing is growing in nuclear physics, especially in the realm of fundamental symmetries research. The basic unit of information in a quantum computer is a quantum bit, or qubit. Unlike classical bits, which can be in one of two states—0 or 1—a qubit can be in a superposition of states. In other words, the value of a qubit can be some simultaneous mixture of 0 and 1. Classical bits are sensitive to naturally occurring radiation such as cosmic rays. The problem is well managed in modern classical computers with error correction schemes that can detect and fix bit flips caused by cosmic rays.

In the last few years, several interdisciplinary groups of nuclear physicists and quantum information scientists have observed the deleterious effects of normal background radiation in superconducting qubits (Figure 1). Electrons in a superconductor pair up in a way that allows them to carry current without resistance. Unfortunately, the pairs are easily broken by the energy from ionizing radiation, and the resulting individual electrons can collapse the delicate quantum state. In qubit devices that have been exposed to elevated radiation, the lifetime of quantum states is limited to a few milliseconds—far shorter than what is needed for most quantum computing algorithms. Furthermore, observations of devices with many qubits on a single chip show that radiation-induced errors tend to occur in many qubits at once. Unfortunately, effective quantum error correction schemes require that qubit errors are completely uncorrelated. Active collaborations across disciplines are working now to mitigate these radiation-induced effects. The efforts include shielding qubits from radiation—including by operating them underground—exploring designs that are less sensitive to radiation, and developing error-rejection schemes that directly detect radiation events and veto operations occurring shortly afterward.

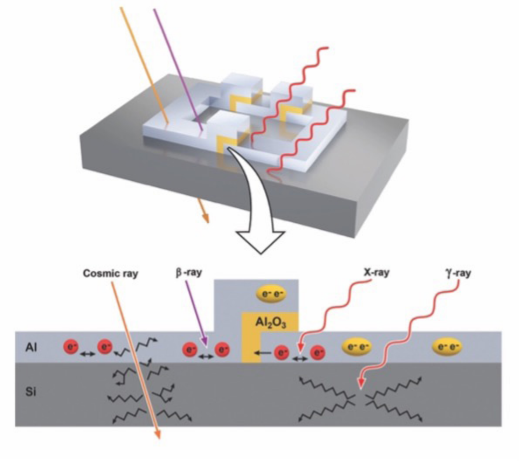


Figure 1: Schematic of radiation interactions in a superconducting qubit. Different types of radiation interact in different parts of the device, but they all deposit energy that spreads throughout and eventually into the superconductor (aluminum in this device). Energy in the superconductor can break pairs of electrons (yellow) into individual electrons (red). Individual electrons can upset the qubit state when they tunnel through the Josephson junctions (yellow, Al_2O_3) [S48].

behind a possible signal pose a grand challenge and an opportunity for theoretical research. Building on progress since the last Long Range Plan, theorists across traditional discipline boundaries (nuclear physics, particle physics, and cosmology) are poised to understand the signatures of lepton-number-violating mechanisms across a wide range of phenomena: from the generation of matter in the early universe, to processes at the Large Hadron Collider (LHC), to nuclear neutrinoless double beta decay. Given the many energy scales involved, this problem is particularly challenging and will require using a broad spectrum of theoretical and computational techniques. The ultimate goal is to predict the decay rates with quantified uncertainties, as induced by a broad class of lepton-number-violating mechanisms.

Experiments to observe neutrinoless double beta decay are crucial and challenging. If an experiment shows evidence for the decay—a result that should earn a Nobel Prize—then confirmation will be necessary. An observation in more than one isotope, each with significantly different detector uncertainties, will provide that confirmation. However, the long time frame for construction and operation demands that multiple experiments be pursued simultaneously. The US program must therefore include complementary experiments studying different isotopes with different detection techniques. Furthermore, searches in multiple isotopes will mitigate the effect of theoretical uncertainties in the nuclear matrix elements that may result in overestimating the decay rate for a particular isotope. Ultimately, observation in multiple isotopes will be necessary to unravel the underlying physics that mediates neutrinoless double beta decay.

From the point of view of experimental uncertainties, the biggest challenge is separating the neutrinoless double beta decay signal from backgrounds. Primary backgrounds are caused by cosmic rays; the associated two-neutrino decay; and trace amounts of radioactivity in the detector, its construction materials, and the surrounding environment. To escape natural cosmic radiation, all experiments must be executed deep underground at a site like SNOLAB in Sudbury, Ontario, Canada or Gran Sasso National Laboratory (LNGS) in Italy. Very good energy resolution helps distinguish neutrinoless double beta decay from the otherwise inescapable two-neutrino double beta decay, as shown in Figure 6.4. Detector materials are chosen or even manufactured specifically to have very low intrinsic radioactivity from common sources like potassium, uranium, thorium, and their decay products. Each experiment then employs ingenious and unique methods to further reduce backgrounds with minimal effect on signal sensitivity. Common schemes include shielding against radiation using both passive and active shields, the latter consisting of sensitive detector materials that flag the presence of background in the data. Experiments can also use details of the electrical signal pulses in their detectors to further discriminate signal from background.

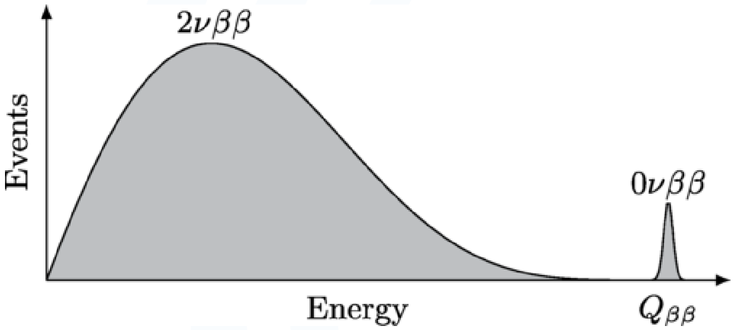


Figure 6.4. The expected signal of neutrinoless double beta decay ($0\nu\beta\beta$) and the inescapable background from the Standard Model allowed two-neutrino double beta decay ($2\nu\beta\beta$). *The neutrinoless double beta decay peak is shown with 1.5% energy resolution and is arbitrarily enlarged in height for visibility [25].*

Following the release of the 2015 Long Range Plan, an NSAC subcommittee report listed several recommendations and goals related to R&D challenges for some of the key US neutrinoless double beta decay experimental efforts. These goals have now been achieved. Half-life limits exceed 10^{26} years, 10 times longer than those achieved by the time of the last Long Range Plan in 2015. Technology demonstrators for several candidate isotopes, summarized in Table 6.1, have proven the principles required for successful next-generation ton-scale searches. The Germanium Detector Array (GERDA) and Majorana experiments used high-purity enriched germanium detectors, which provide very low levels of background events; the Enriched Xenon Observatory (EXO)-200 experiment used liquid xenon, which provides a large enriched isotopic mass coupled with particle tracking; the Cryogenic Underground Observatory for Rare Events (CUORE) used tellurium crystals, which have extremely good energy resolution; the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)-Zen experiment used liquid scintillator loaded with enriched xenon, providing excellent rejection of backgrounds from sources outside the active volume.

Great progress has been made on various theoretical fronts.The connection among lepton-number violation in nuclear decays, high-energy collider processes, and early universe evolution has been sharpened. Scenarios in which collider signals complement nuclear searches and can falsify matter-producing mechanisms have been identified. A framework has been developed to study the manifestations of a broad variety of lepton-number violation mechanisms in nuclei. First-principles nuclear structure calculations have progressed and have been successfully tested in single beta decay, solving a long-standing puzzle related to the over-prediction of Gamow–Teller transitions. All these developments have paved the way toward theoretical predictions of neutrinoless double beta decay rates with quantified uncertainties.

The stage is now set for the presently recommended ton-scale neutrinoless double beta decay experiments. The community has rallied around three candidates.

Experiment	Isotope	Half-life limit (10^{26} years)	mββ limit (meV)
MAJORANA	Germanium-76	0.83	113–269
GERDA	Germanium-76	1.8	79–180
EXO-200	Xenon-136	0.35	93–286
KamLAND-Zen	Xenon-136	2.3	36–156
CUORE	Tellurium-130	0.22	90–305

Table 6.1. Technology demonstrators

6.3.1. Discovery opportunities at the ton scale

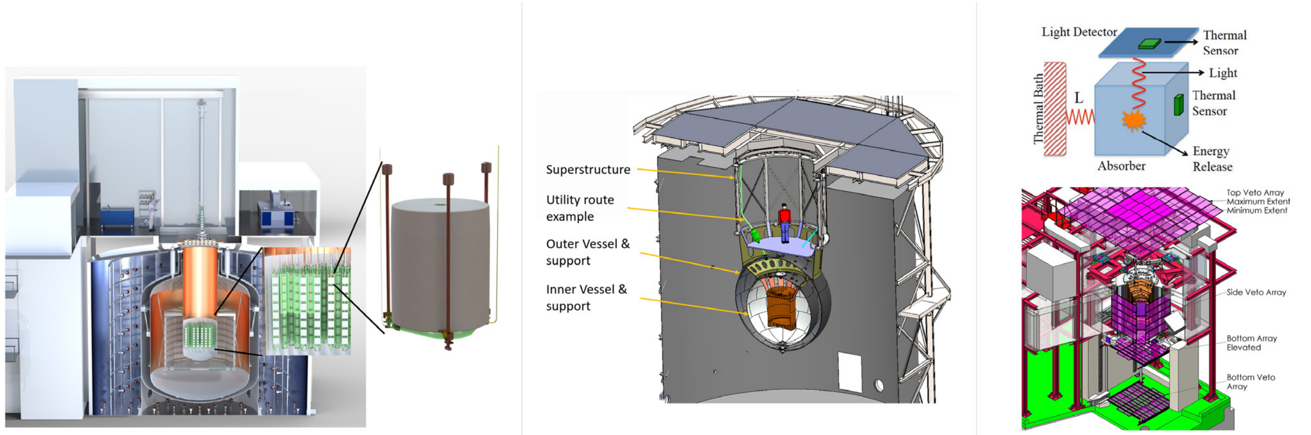
To maximize the discovery potential for neutrinoless double beta decay at the ton-scale, the proposed US program consists of three experiments, fielding very different detection technologies and using three different isotopes: the CUORE Upgrade with Particle Identification (CUPID; molybdenum-100), the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay–1,000 kg (LEGEND-1000; germanium-76), and the next-generation Enriched Xenon Observatory (nEXO; xenon-136). These three experiments have undergone a rigorous DOE portfolio review, are ready to start construction, and are actively preparing for the Critical Decision (CD) process. All three experiments probe neutrino masses all the way to the lower limit allowed by the so-called inverted ordering of neutrino masses, as shown in Figure 6.5. The following subsections detail these experiments.

6.3.1.1. LEGEND-1000

The LEGEND experiment takes advantage of the intrinsically excellent energy resolution of high-purity germanium detectors. In LEGEND's design, detectors are enriched to 90% in the neutrinoless double beta decay candidate isotope germanium-76. The Majorana Demonstrator proved the excellent energy resolution and background rejection capabilities of large inverted coaxial point-contact (ICPC) high-purity germanium detector geometries. Approximately 330 ICPC detectors weighing 3 kg each comprise the 1,000 kg of LEGEND-1000. They are housed in strings of about six detectors each, and each string is immersed in liquid argon that is extracted from deep underground and therefore depleted in the cosmogenic isotope argon-42 that would otherwise be a background source. All materials near the detector are selected with stringent radiopurity requirements. Copper parts are electroformed by a process designed specifically to exclude radioactive contaminants. The underground argon is separated from a larger quantity of ordinary (atmospheric-sourced) liquid argon by more electroformed copper, and the entire volume is surrounded by water to provide additional suppression of backgrounds coming from the outside.

Large ICPC detectors can discriminate signal from background by analyzing event pulse shapes; charged particles like alphas interact near the surface, resulting in slowly rising pulses, whereas more penetrating gammas in the bulk of the detector are likely to interact in multiple locations, distorting the measured signals and distinguishing them from neutrinoless double beta decay events, which deposit all energy in a single location in the bulk. Because neutrinoless double beta decay events are inherently single-site events, further background reduction is possible by rejecting events in which more than one detector, or the surrounding liquid argon, registers energy. Penetrating cosmic rays can be rejected because of the light they emit while traversing the liquid argon baths, both of which are instrumented as active veto detectors.

LEGEND aims to increase the half-life sensitivity for neutrinoless double beta decay of germanium-76 in a first phase (LEGEND-200) to 10^{27} years, and in a



LEGEND nEXO CUPID

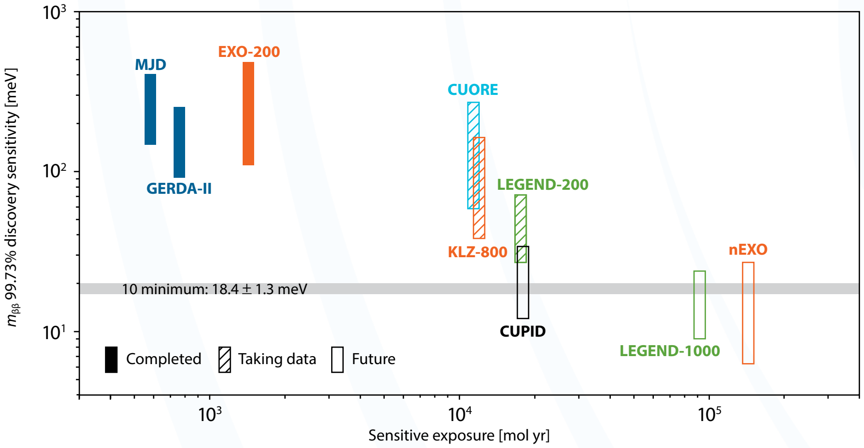


Figure 6.5. The ton-scale neutrinoless double beta decay experiments described in the text: LEGEND-1000, nEXO and CUPID. *The plot shows the results of past experiments (solid), the projected reach of currently running experiments (hatched), and future ton-scale experiments (open). The recommended ton-scale experiments probe the inverted ordering (gray band). Concepts for experiments beyond the ton scale to probe even further are discussed in the text [26].*

second phase (LEGEND-1000) to 10^{28} years. Those numbers represent the 90% confidence level half-life limit that would be set if no signal appears, or the half-life that would result in a 50% chance for a significant signal at three standard deviations of significance. LEGEND-200 is already operating 200 kg of germanium detectors in an upgrade of existing GERDA experiment infrastructure at the LNGS laboratory in Italy. LEGEND-200 is collecting physics data at the time of this writing.

6.3.1.2. nEXO

The nEXO apparatus is a time-projection chamber (TPC) with 5 tons of liquid xenon (LXe) enriched to 90% in the neutrinoless double beta decay candidate xenon-136. The choice of LXe is motivated by the ability of large homogeneous detectors to identify and measure background and signal simultaneously. The nEXO experiment builds on the success of EXO-200, the 200 kg demonstrator experiment that produced landmark results. The approach takes maximum advantage of the large linear dimensions compared with the mean free path of background gamma radiation. The nEXO TPC consists of a single cylindrical volume of LXe that is instrumented to measure both ionization (charge) and scintillation (light) signals in the LXe with excellent energy resolution and strong background rejection. Energy reconstruction, event topology (single vs. multisite interactions), position reconstruction, and scintillation/ionization ratio are combined using traditional and deep-learning tools to effectively discriminate between signal and backgrounds. Information on particle interactions provided by the TPC and surrounding instrumented shielding give several additional means to reject backgrounds and improve confidence in a potential discovery.

Background projections for nEXO are grounded in existing radioassay data for most component materials and detailed particle tracking and event reconstruction simulations. This approach was validated by EXO-200, where the measured backgrounds closely matched the predictions. Based on these detailed evaluations, nEXO is projected to reach a half-life sensitivity of 1.35 × 10^{28} years (90% confidence level), covering the entire inverted ordering parameter space, along with a significant portion of the normal ordering parameter space. The liquid target enables continuous purification, thus reducing risk of unexpected internal backgrounds, and has several other unique advantages if a discovery occurs. For example, nEXO could directly verify a putative discovery via a blank measurement by swapping the enriched xenon with natural or depleted xenon. Alternatively, the enriched target could be reused with a different detector technology (e.g., a discovery with nEXO may be followed by an investigation of electron energy and angular correlations in a gas TPC).

6.3.1.3. CUPID

The CUPID experiment, an upgrade to the currently operating CUORE experiment at LNGS, aims to search for neutrinoless double beta decay in molybdenum-100 in the region of the inverted mass ordering. The proposed CUPID experiment leverages the extensive existing cryogenic and technical infrastructure built for CUORE. The baseline design for CUPID features an array of 1,596 scintillating crystal bolometers and 1,710 light detectors, each instrumented with germanium neutron-transmutation-doped sensors, a simple cryogenic quantum sensor. The crystals are organized into 57 towers. This technology provides exquisite energy resolution, and the combination of the heat and scintillation light signals allows for efficient rejection of backgrounds owing to alpha particles. The total isotopic mass of CUPID will be 240 kg of molybdenum-100. The experiment will have discovery potential in the entire inverted hierarchy region of neutrino masses. CUPID will set a half-life limit of 1.4×10^{27} years (90% confidence level) if no signal is observed, or it will detect a signal at three standard deviations of significance as low as 1.0×10^{27} years.

Reusing the existing CUORE cryostat allows for an economical deployment of CUPID and builds on the success of years of stable CUORE operations and a detailed understanding of the backgrounds from the cryostat. The light and thermal readout has been demonstrated by several prototype experiments. Bolometric detectors are scalable, allowing gradual, phased deployment. In the case of a putative discovery, crystals based on different isotopes could be installed. The isotopic flexibility and scalability also make bolometers an interesting technology for beyond the ton-scale efforts.

In all these cases, the search for neutrinoless double beta decay is an international effort (Sidebar 6.1).

6.3.1.4. Looking beyond the ton scale

If the ton-scale neutrinoless double beta decay program does not reveal evidence for neutrinoless double beta decay, then new experiments with even greater sensitivity will be needed. By contrast, if neutrinoless double beta decay is discovered by one or more ton-scale experiments, then the question will turn to determining the mechanism for neutrinoless double beta decay and whether light Majorana neutrinos are the only mediators of this process.

The candidate ton-scale experiments—CUPID, LEGEND-1000, and nEXO—have explored future plans that would allow scalability beyond the ton-scale. Other possible beyond-ton-scale experiments are NEXT, which will employ high-pressure xenon gas TPCs with barium tagging; Theia, a large-scale hybrid Cherenkov/scintillation detector that will be an outgrowth of the SNO+ and KamLAND-Zen experiments; and Selena, which will employ high-resolution amorphous selenium/complementary metal-oxide semiconductor devices with electron imaging capabilities. With novel techniques and sensor technologies, rich reconstruction of event topologies, and advanced particle identification, these experiments will be sensitive to half-lives longer than 10^{28} years. The new detection capabilities of this future generation will also provide access to a wider physics program, including tests of combined charge, parity, and time-reversal symmetry and baryon-number-violation tests, precision low-energy solar neutrino measurements, and the possible study of supernova neutrinos.

6.4 ELECTRIC DIPOLE MOMENTS

A nonzero permanent EDM of a particle or system of particles with a unique lowest energy state would break both parity and time-reversal symmetries or charge–parity symmetry because the product of all three symmetries is conserved. A permanent EDM (henceforth just "EDM" if not specified otherwise) is proportional to its internal spin, and it is nonzero if the system's energy changes linearly in an applied electric field. These features distinguish it, in principle, from an EDM induced by an electric field, which does not break charge–parity symmetry. Although charge–parity symmetry is not a symmetry of the Standard Model, the EDMs of electrons, neutrons, nuclei, and molecules predicted from this mechanism are all so extraordinarily small that studies of such systems at the sensitivities anticipated over the time scale of this Long Range Plan probe BSM sources of charge–parity symmetry violation. New sources of charge–parity symmetry violation have long been thought to be key to explaining the cosmic matter–antimatter asymmetry, but a failure to detect them would also be revealing, pointing to other mechanisms that possibly involve dark-sector particles. The EDMs of the various possible systems probe BSM physics in distinct but complementary ways. Each of these potential EDM candidates is studied experimentally. Of those, neutrons, nuclei, and radioactive molecules are under the purview of nuclear physics. This section explores their possibilities.

Sidebar 6.4 Nuclear Decay and Quantum Sensors: From Neutrinos to Safeguards

The application of emerging quantum technology in nuclear science provides an exceptionally powerful environment in which to make new discoveries. Leading the charge are experiments to search for new descriptions of neutrinos that may help elucidate the origin of matter in the universe. These methods, such as the CUPID experiment to search for neutrinoless double beta decay in molybdenum-100, require unprecedented sensitivity that these state-of-the-art sensors can provide (Figure 1). The CUPID technology uses molybdenum-based scintillating crystals instrumented with quantum-enabled sensors to measure both light and the microscopic heat signature created in a single decay event—providing exquisite energy resolution and particle identification.

Other experiments have developed superconducting quantum sensors that are sensitive enough to measure the tiny energy kick that a lithium atom gets from the neutrino following beryllium-7 electron-capture decay. The Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment currently performs such precision decay measurements to observe tiny changes in the observed recoil energies (Figure 1). These changes could be caused by a hypothetical new type of neutrinos: so-called sterile neutrinos. BeEST has set world-leading laboratory-based limits on whether these sterile neutrinos, which are candidates for dark matter, can have masses below 1 MeV.

The same techniques that were developed for fundamental science have now begun to percolate into nuclear applications for safeguards and nonproliferation. Superconducting microcalorimeters have already been harnessed to provide dramatically improved capabilities to quantify fissile and fissionable isotopic inventories. Members of the International Nuclear Safeguards Engagement Program in the NNSA, several national laboratories, and the US Nuclear Data Program are now collaborating to use these sensors to improve decay data for the most critically important isotopes. The results of this work have already enhanced domestic and international security and promise improved fission product yield data with continued development in this area.

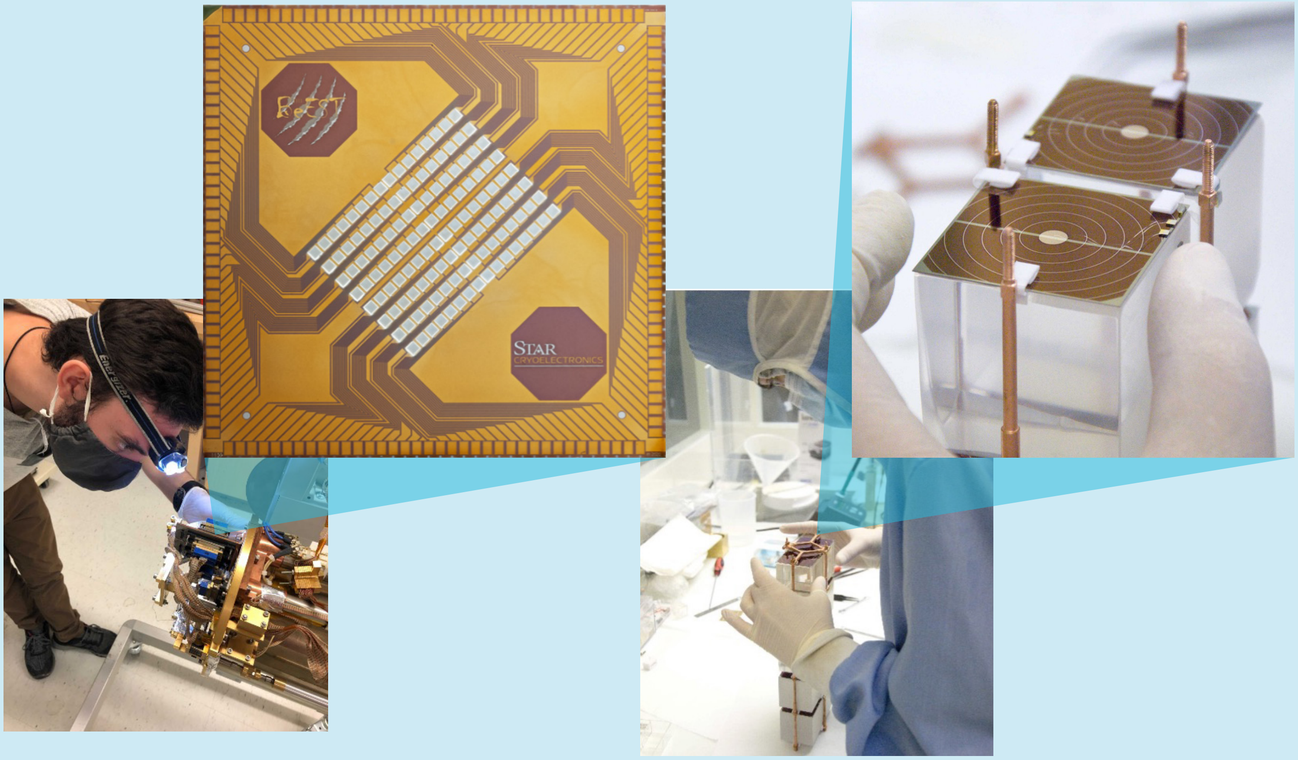


Figure 1. (left) A microscope image of a 128-pixel aluminum-based superconducting tunnel junction array prototype for Phase-IV of the BeEST experiment. This type of array is implanted with large doses of radioactive beryllium-7 and operated at near absolute-zero temperatures to search for exotic new physics [S49-50] . (right) A CUPID scientist assembling cryogenic sensors based on scintillating crystals for quantum-enabled light detection [S51-52].

Theory is crucial for the interpretation of any EDM discovery, and recent progress on different fronts bodes well for the coming years. Significant progress has been made toward connecting possible BSM sources of charge–parity symmetry violation to concrete mechanisms for generating the baryon asymmetry in the early universe and the observable EDMs. In particular, lattice QCD calculations (Sidebar 3.1) for the nucleon (neutron and proton) EDMs have become possible, paving the way for future studies to yield results with quantified uncertainties. Progress has also been made toward computing the size of the nucleon EDM from charge–parity symmetry violation in the strong interaction, which may stem from distinct BSM sources. Similarly, progress in nuclear structure makes first-principles calculations of nuclear EDMs a realistic prospect on a somewhat longer time scale. The sensitivity and sophistication of the combined theoretical and experimental studies open new windows on BSM charge–parity symmetry violation far beyond the energy reach of direct searches for new particles.

6.4.1. Neutron EDM

A discovery of a neutron EDM (nEDM) will be paradigm shifting. Searches for an nEDM started in the 1950s, but it has not yet been discovered. Multiple efforts around the world are ramping up to push the precision frontier with nEDM experiments, enabled by new facilities for intense ultracold neutron (UCN) production. Two are in the United States, including the world's most ambitious at the Spallation Neutron Source (nEDM@SNS), with a projected sensitivity of 3×10^{-28} e-cm, approximately two orders of magnitude below the current limit. Over the last Long Range Plan period, the nEDM@SNS project has moved from feasibility demonstrations to construction of the apparatus. A second nEDM effort at Los Alamos National Laboratory (LANL) has achieved the polarized UCN density required for its sensitivity goal, 3×10^{-27} e-cm, which would be a world-leading result (until the completion of nEDM@SNS).

To overcome the statistical bottleneck, the nEDM@SNS experiment undertakes large-scale cryogenic engineering challenges to make innovative use of superfluid helium. It uses the Fundamental Neutron Physics Beamline (FNPB) at SNS, where a beam of cold neutrons scatter in superfluid helium-4 to produce UCNs in the measurement cells, as shown in Figure 6.6. This system allows for a relatively high density of UCNs to be produced without transport losses—a major improvement over other nEDM experiments. Magnetometry is possible via superconducting quantum interference device (SQUID) quantum sensors that measure the time-dependent magnetization of the polarized helium-3, while the UCN frequency is monitored via the spin-dependent neutron–helium-3 capture reaction that produces scintillation light from the reaction products. The frequency of neutrons spinning in a magnetic field will be measured to a precision of a few parts per billion.

Achieving this EDM precision requires exquisite control of systematic uncertainties. The SNS experiment has developed two independent techniques to measure the EDM signal: (1) a direct frequency measurement monitors the beating of spin precessions between UCNs and helium-3 and (2) a linear change in the neutron capture rate directly measures EDM using a dressed spin technique, in which a radio frequency field is applied to lock the spin precessions of UCNs and helium-3 in phase. These new capabilities allow nEDM@SNS to quantify the effects of environmental magnetic fields that would otherwise give rise to false EDM signatures. The experiment construction will be completed during this Long Range Plan period to start a physics measurement program.

6.4.2. Atomic and molecular EDMs

Experiments using methods of atomic, molecular, and optical (AMO) physics are making a major contribution to the search for BSM charge–parity symmetry violation. They are poised to expand both in breadth and depth by studying nuclei in atoms and molecules. The nuclei in suitable candidate systems are sensitive to underlying charge–parity symmetry violating interactions, but their Schiff moments and magnetic quadrupole moments vary across different nuclei and probe new charge–parity symmetry violating sources in a manner complementary to those probed by the neutron (and proton) EDMs.

Several AMO experiments to search for nuclear charge–parity symmetry violation are in development. The methods and species are wide ranging and include atoms (radium-223, radium-225, xenon-129, mercury-199, and ytterbium-171) and molecules (^{173}YbOH, and ^{205}TlF), although broader possibilities exist. Different species provide critical complementary information about different underlying mechanisms for nuclear charge–parity symmetry violation, and using different methods mitigates systematic uncertainties. Numerous experiments with atoms have completed searches and published new EDM limits. The Radium EDM experiment at Argonne has the potential to improve upon its established limit by several orders of magnitude in the near future.

Heavy nuclei with mass numbers larger than about 220 can be nonspherical, and, in certain cases, a reflection-asymmetric, permanent octupole deformation can exist—and those radioactive isotopes can have greatly enhanced nuclear moments. In particular, the Schiff moment in systems such as radium-225 or protactinium-229 provides a striking enhancement of time-reversal symmetry violating effects by a factor of 100–1,000 (radium-225) or more (protactinium-229) over mercury-199.

Several major developments are enabling this new generation of experiments, which are achieving rapidly improving sensitivity. One is the improved ability to control the quantum states of molecules by using methods like those developed during the last few decades for atomic systems. This capability in turn enables harnessing the 3–4 order-of-magnitude amplification of charge–parity symmetry violating signals in polar molecules. This amplification is associated with polar molecules’ large internal electric field compared with atoms. Molecules also offer new controls over systematic uncertainties that are unavailable in atoms. It is increasingly realistic to combine both molecular and nuclear amplification factors to achieve many orders of magnitude of improved sensitivity to nuclear charge–parity symmetry violation effects. The ongoing advances in precision molecular experiments, coupled with the anticipated availability of these molecules at FRIB (Sidebar 6.2), present unique opportunities to the research community in fundamental symmetries within the United States.

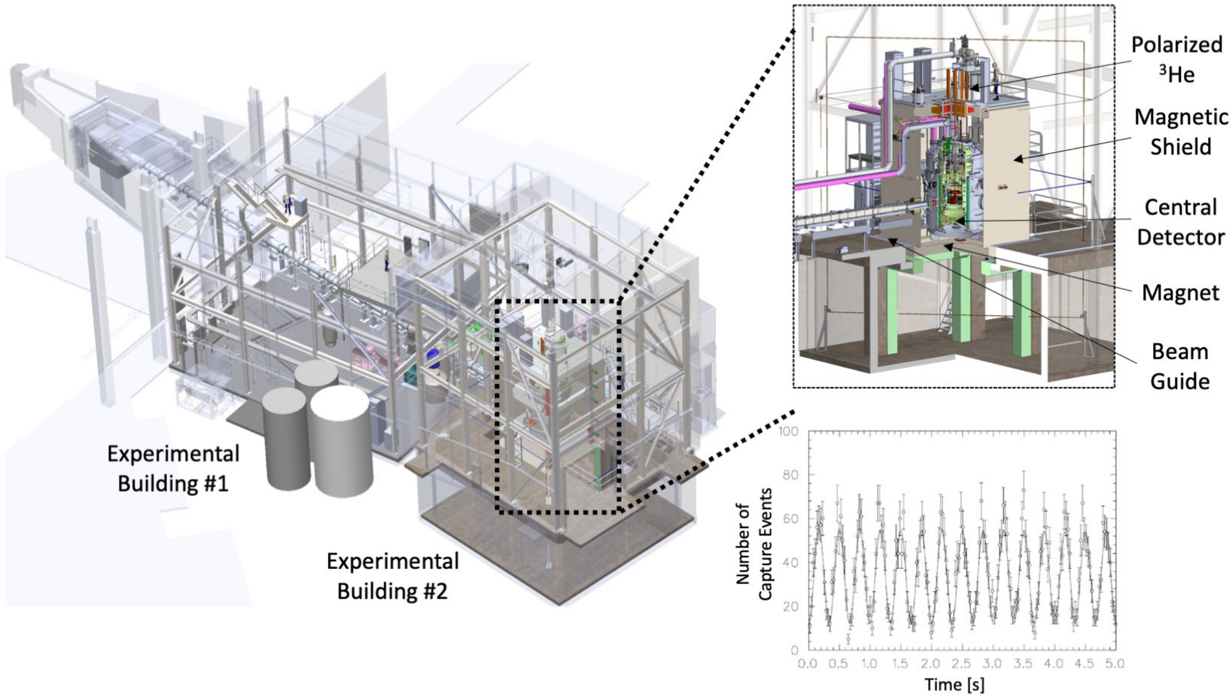


Figure 6.6. The nEDM@SNS apparatus in construction at Oak Ridge National Laboratory. *(left) Layout of the nEDM@SNS experiment on the Fundamental Neutron Physics Beamline at the Spallation Neutron Source at Oak Ridge National Laboratory. (upper right) Rendering of a close-up of the experimental apparatus (note for scale the human in the upper region of the apparatus). (lower right) Simulation of the experimental signal from neutron-helium-3 capture events oscillating at the neutron-helium-3 beat frequency for a magnetic field setting of 30 mGauss [27].*

6.5 PRECISION TESTS OF THE STANDARD MODEL

6.5.1. Muon magnetic moment

Precision studies of the magnetic properties of particles provide powerful tests of the Standard Model. The muon magnetic moment, which controls the behavior of a spinning muon in a magnetic field, can be computed in the Standard Model with a precision that is better than the part-per-million (ppm) level. Owing to the leadership and significant technical contribution of nuclear scientists, we are in the midst of a campaign to measure the muon magnetic moment with precision that approaches 0.1 ppm with the Muon g-2 Experiment at Fermilab. A major highlight since the last Long Range Plan is the success of the Fermilab experiment, which has reported results on a portion of their data to a precision of 0.2 ppm. If one were to compare to the 2020 theory initiative prediction, a five standard deviation exists, representing a tantalizing hint of the existence of new particles and interactions. Ongoing experimental and theoretical work during this Long Range Plan period should clarify the current story.

The Muon g-2 experiment was completed in 2023. When the full dataset is analyzed, the collaboration expects to reach or exceed its precision goal of 0.140 ppm. In parallel, the precision of the Standard Model calculation is expected to improve to a level nearly commensurate with experiment. The key contribution arising from quantum fluctuations of a photon into hadrons will be addressed via two independent theoretical methods. If the improved Standard Model theoretical estimate evolves toward agreement with the experimental value, then this result will strongly constrain possible new physics scenarios. Conversely, if the central values of theory and experiment remain stable, then this precision test will suggest new physics.

6.5.2. Weak nuclear force

Precision studies of electroweak interactions constitute one of the major frontiers in subatomic physics and may soon reveal tears in the Standard Model fabric. Nuclear physics experiment and theory provide an excellent landscape to search for additional, more feeble contributions to the weak interaction that could signal new physics in our universe. Standard Model weak interactions are responsible for quarks changing their identities, which is the basis for nuclear transmutation. The nuclear weak forces are characterized by their symmetry properties—two components, labeled vector and axial vector, denote how they transform under parity inversion. Other hypothetical weak interactions such as scalar and tensor forces may also be present as small contributions. Such contributions can be observed as small deviations of the predicted behaviors of beta decay products. An intensive effort by the fundamental symmetries community is motivated by the possibility for clean Standard Model theoretical predictions in these decay processes, thus enabling high-precision experimental searches for BSM effects.

We highlight three priorities in precision Standard Model tests to be explored in the beta decays of neutrons, nuclei, and mesons:

1. To firmly and consistently establish the largest element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix with precision of a few parts in 10,000 in both neutron and nuclear decay.

2. To search for tensor and scalar components of the weak interaction with sensitivity similar to complementary processes at the LHC.

3. To perform the most stringent test of the lepton universality of weak interactions (i.e., electrons and muons participate in weak disintegrations with identical strength) by studying rare pion decays.

Furthermore, parity-violating electron scattering (PVES) can determine the full extent and validity of the Standard Model electroweak interaction and search for new physics from MeV to TeV scales by comparing measurements well below the electroweak symmetry–breaking scale to accurate theoretical calculations.

6.5.2.1. Nuclear and neutron beta decay

Studies of beta decay are powerful probes of BSM physics thanks to the extreme precision and accuracy that can be achieved in both theory and experiment. Beta decay observables such as total decay rate, electron energy spectra, and angular correlations between emitted particles carry information about the nature and properties of the underlying weak force mediator. Weak interactions in the Standard Model are mediated by the W boson, a particle with mass about 80 times larger than that of the proton. Precision studies of beta decays can reveal the imprint of new feeble forces, including scalar and tensor forces, associated with hypothetical carriers much heavier than the W boson. Such contributions would be observed as small deviations from Standard Model predictions. Conclusions from these studies are often independent of a particular model; therefore, they facilitate evaluating the increasing landscape of anomalies in precision Standard Model tests. Figure 6.7 illustrates some anomalies that involve nuclear and neutron decays.

One such anomaly concerns discrepant determinations of elements of the so-called CKM matrix, which describes how quarks change flavor through weak interactions like beta decay. The CKM matrix is unitary in the Standard Model, meaning that the up- to down-quark interaction strength (V_{ud}^2) and the up- to strange-quark interaction strength (V_{us}^2) should add to unity. Observed violations of CKM unitarity would imply BSM physics. The left plot in Figure 6.7 demonstrates the issue. Concordant measurements consistent with Standard Model requirements of CKM unitarity would have all the colored bands intersecting in a single region that includes the unitarity constraint (black line): the squares of the elements should add to one. The first and largest CKM matrix element, V_{ud}, is determined by nuclear and neutron beta decay. The so-called superallowed beta decay dataset has been refined after decades of careful work, yielding the most precise result for V_{ud} with net uncertainty of 0.03%.

The bands in the left panel of Figure 6.7 rely on both experimental and theoretical input. Since the last Long Range Plan, new theoretical analyses of the interplay of electromagnetic, strong, and weak interactions in beta decay have been the key driver leading to the tension in the unitarity test. Similarly, lattice QCD calculations of neutron-to-proton couplings relevant for neutron beta decay have reached percent-level precision, and new radiative corrections to this ratio were identified. Looking to the future, it will be essential to further improve the theoretical predictions of beta decays using complementary techniques and explore BSM scenarios that may be responsible for the CKM tension, should it persist.

Free neutron decay is a theoretically clean approach to precisely determine V_{ud} because it is not subject to large nuclear structure-dependent corrections. A competitive determination of V_{ud} from neutron decay requires experimental uncertainties of 0.03% in the ratio of weak axial-vector to vector coupling strengths and 0.3 second precision in the neutron lifetime. Upcoming neutron decay experiments will measure the ratio of coupling strengths to less than 0.1%. The neutron "a" and "b" (Nab) experiment at SNS will attain 0.04% precision, and a proposed modest upgrade, called pNab, aims to reach 0.02%. Plans are underway to upgrade the existing Ultracold Neutron Asymmetry (UCNA) experiment at LANL to UCNA+ with an upgraded detector package and higher UCN densities now available for sensitivity comparable to Nab.

Discordant measurements of the neutron lifetime (Figure 6.7, right) are another vexing anomaly in precision Standard Model tests. The beam method, which measures neutron decays in flight by counting the decay products, has obtained a larger value compared with UCN traps that count surviving neutrons after some holding time. These two leading methods disagree by 10 s (almost 5 standard deviations)—a serious stumbling block to improved overall precision. Planned US-based neutron lifetime experiments will be able to resolve the beam–bottle neutron lifetime discrepancy and improve the global uncertainty in the neutron lifetime to less than 0.3 s. The UCNτ experiment recently obtained the most precise measurement of the free neutron lifetime, with uncertainty of 0.35 s, and its upgrade UCNτ+ will use a new adiabatic transport technique to load its magnetic trap to approach 0.1 s precision. The UCNProbe experiment at LANL will employ a novel hybrid beam–bottle method to directly address the discrepancy. The Beam Lifetime 3 (BL3) experiment at NIST is a next-generation beam experiment that will exhaustively explore and test systematics of the method with much higher statistics and will obtain better than 0.3 s precision on the lifetime.

During the last Long Range Plan period, significant investments in rare-isotope beam (RIB) production capabilities as well as dedicated development of measurement techniques have enabled studies that can probe new physics at the tens of teraelectronvolt energy scale—complementary to, and even higher than, the LHC at the European Organization for Nuclear Research (CERN). Improved limits on tensor

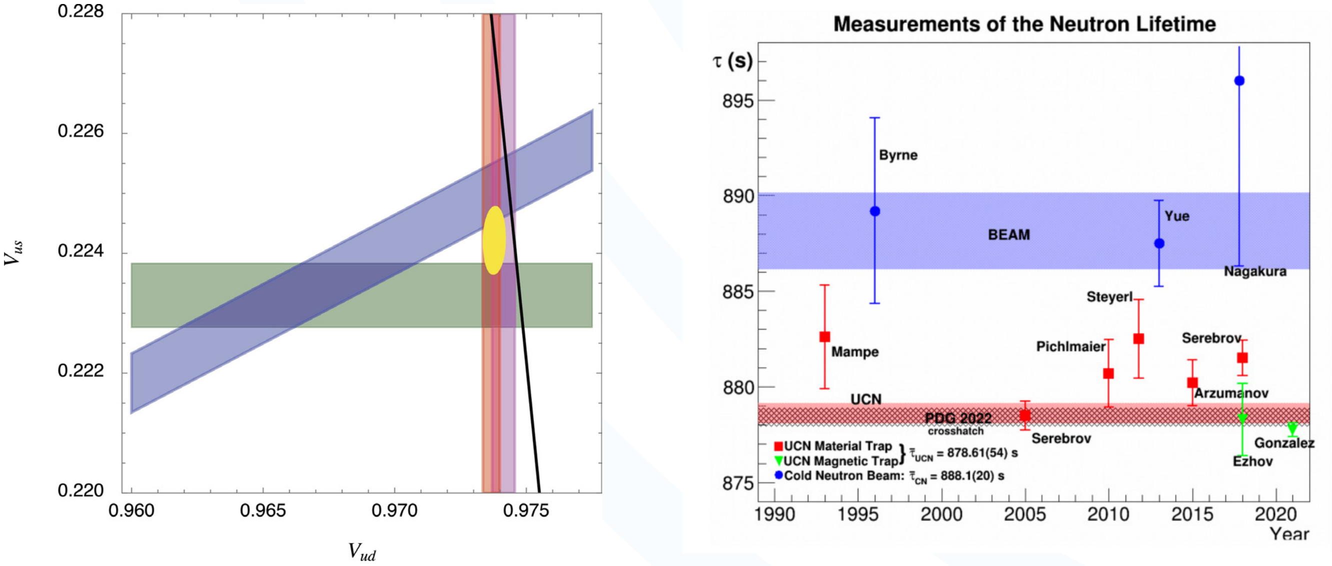


Figure 6.7. Current anomalies in nuclear and neutron decay. *(left) Measurements of the CKM matrix elements* V_{ud} *and* V_{us} *using nuclear, neutron, and two types of kaon decays (red, pink, green, and blue, respectively). The yellow ellipse is a global fit, and the black line represents the relationship assuming CKM unitarity. In a world of harmonious experiments described by the Standard Model, these should all intersect at a single point. Something is amiss. (right) Most recent and/or precise measurements of the neutron lifetime. Measurements using trapped UCNs (red squares and green triangles; red band shows the average) determine a significantly shorter lifetime than beam-based measurements (blue squares and band). The observed discrepancy of 10 s could not be explained with known theory [28].*

weak forces in helium-6 and lithium-8 decay using the ATLAS Beta Paul Trap have achieved less than 1% of the usual weak interaction strength. Tensor interactions can appear as modifications to precisely measured beta spectra via a particular BSM mechanism called Fierz interference. UCNA has produced the first direct limits on Fierz interference, and Nab will improve upon that sensitivity in the coming years. The cyclotron radiation emission spectroscopy (CRES) technique, introduced as a promising way to determine neutrino mass by the tritium endpoint method, has now been used by the He6-CRES experiment to observe decays of helium-6 and neon-19. The technique is being developed to further improve searches for tensor interactions via Fierz interference in those decays.

With improved RIB access and significant advancements in nuclear theory, the US beta decay community is poised to capitalize on decades of plans and development in this area. This field has several high priorities, most notable of which are tantalizing hints of new physics that have arisen through discrepancies that violate the unitarity condition of the CKM matrix. A dedicated collaborative effort within the community will address this essential area. Furthermore, the same nuclear systems which allow for precision studies of CKM unitarity also serve as sensitive laboratories for exotic new physics searches, such as new fundamental particles, or BSM couplings in the weak interaction. Measurements of these case-specific nuclei (e.g., helium-6, carbon-10, oxygen-14) will push these searches for new physics beyond the 0.1% precision level using state-of-the-art experimental techniques such as atom/ion traps, superconducting quantum sensors, and CRES.

6.5.2.2. Pion weak decays

Weak decays of the charged pi meson (pion) offer particularly pristine probes of (1) lepton flavor universality (i.e., the equality of weak couplings for different generations of leptons) via the pion electronic decay and (2) the V_{ud} element of the CKM matrix, via the pion beta decay, without nuclear structure corrections and uncertainties. Although theoretically cleaner than similar nuclear processes, the electronic and beta decays occur with extremely low probabilities, or branching ratios, of order 10^{-4} and 10^{-8}, respectively, hindering their experimental study. Building on the experience of prior experiments PiBeta, PEN, and PiENu, a new PIONEER collaboration has assembled to push for an order-of-magnitude increase in the experimental precision of the electronic branching ratio, 3–5-fold improvement of the beta-decay branching ratio, and 10-fold improvements in sterile neutrino search sensitivity, in a staged approach. The experiment has been approved at the Paul Scherrer Institute in Switzerland. The project, whose ultimate horizon exceeds the range of this Long Range Plan, is presently focused on the R&D effort needed to make the ambitious program possible.

6.5.2.3. Hadronic parity violation

Parity violation in low-energy processes with nucleons and nuclei, the so-called hadronic parity violation, is expected in the Standard Model. Its study has been difficult because of the strongly coupled nature of neutrons and protons (nucleons) in the low-energy regime as well as the challenging nature of the experiments. After many years of effort, two experiments have been completed, finding suggestive evidence for hadronic parity violation in relation to polarized cold neutron capture on protons (NPDGamma) and on helium-3 nuclei at SNS. Both experiments control combined statistical and systematic errors at about the 10 parts per billion (ppb) level. The result from the NPDGamma experiment provides the first direct evidence for parity-violating one-pion exchange in the nucleon–nucleon interaction. Ongoing and future hadronic parity violating studies, both theoretical and experimental, aim to further characterize the parity-violating nucleon–nucleon interaction.

6.5.2.4. Parity violating electron scattering

The Measurement of a Lepton–Lepton Electroweak Reaction (MOLLER) and SoLID experiments plan to measure PVES asymmetries with the 11 GeV electron beam at Jefferson Lab (Sidebar 3.9). They represent special opportunities to probe BSM physics, each with a unique window to new physics from MeV to multi-TeV scales. They are part of a multifaceted strategy to determine the full extent of validity of the electroweak theory and search for new physics via indirect probes, where ultraprecise measurements of electroweak observables at energy scales well below that of high-energy colliders are compared with accurate theoretical predictions. Theoretical progress in evaluating complete one-loop and leading two-loop effects will allow full exploitation of the planned experimental uncertainty goals.

The parity-violating asymmetry (A_{PV}) is the fractional difference in the electron–target cross section when the polarization of the electron beam is reversed. The MOLLER experiment at Jefferson Lab is designed to measure A_{PV} in polarized electron–electron (Møller) scattering, predicted to be about 33 ppb at the selected kinematics, and the goal is to measure A_{PV} to an uncertainty of 0.8 ppb. The result will yield a measurement of the weak charge of the electron to a fractional uncertainty of 2.4%, achieving sensitivity to new teraelectronvolt-scale lepton–lepton interactions well beyond existing lepton collider and high energy neutrino scattering limits.

SoLID will measure A_{PV} in deep-inelastic electron–quark scattering to a fractional uncertainty of 0.6%. By combining large angular and momentum acceptance with the capability to handle very high data rates at high luminosity, many subpercent-level A_{PV} measurements will be made throughout a wide kinematic range, facilitating the control of uncertainties caused by low-energy hadron dynamics. The extracted linear combination of fundamental quark neutral current couplings will probe teraelectronvolt-scale BSM physics in a region of discovery space inaccessible in high-energy unpolarized proton–proton collisions.

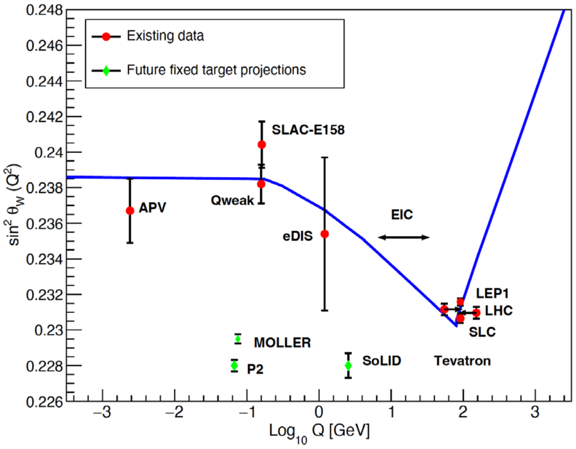


Figure 6.8. Past (red) and planned (green) measurements of the weak mixing angle $\sin^2\theta_w$. *The MOLLER and SoLID experiments will make ultra-precise measurements to challenge theory (blue) at low energies [29].*

Each A_{PV} measurement is typically reported as a measurement of the electroweak mixing angle, a fundamental parameter of the electroweak theory, at the energy scale of the scattering reaction studied. Figure 6.8 shows the best previous low-energy determination of the electroweak mixing angle, including the most precise recent one by the Q-weak experiment, along with the proposed new measurements, MOLLER and SoLID at Jefferson Lab, and P2 in Germany. The ambitious experimental goals are made feasible in part by the progress in experimental techniques developed for the recently completed nuclear weak form factor measurements Lead (Pb) Radius Experiment (PREX) and Calcium Radius Experiment (CREX). The control and correction of the polarization-induced asymmetry in the electron beam at the part-per-billion-level together with the accuracy in monitoring the electron beam polarization at the 0.5% level facilitate MOLLER and SoLID. PREX and CREX have also provided the most accurate constraints on neutron skins in lead-208 and calcium-48, respectively, challenging models of neutron-rich matter and neutron stars (Sidebar 5.2). The slight tension between the two measurements has triggered further theoretical and experimental investigations, in particular motivating the proposed MREX experiment in Germany to improve on the PREX measurement.

6.6 NEUTRINO PROPERTIES

The discovery that neutrinos have tiny nonzero masses is currently the only laboratory-based evidence that the Standard Model is incomplete. Nevertheless, neutrinos remain the most elusive of the known building blocks of our universe, and their properties must be fully characterized. Following this so-called neutrino window into what lies beyond the Standard Model, precision measurements of nuclear decay can elucidate the absolute size of the neutrino masses and can probe the existence of new hypothetical particles, such as the sterile neutrinos. These particles are possibly related to the origin of neutrino mass and may constitute a component of the dark matter in the universe. The following subsections explore opportunities to measure the absolute mass of the neutrino and to detect hypothetical sterile neutrinos.

Neutrino interactions with nuclei are deeply intertwined with many topics in nuclear and particle physics. An accurate description of neutrino scattering from nuclei is required to extract information on neutrino properties from measurements of neutrino oscillations, to learn about astrophysical neutrinos from supernovae and other sources, and to search for BSM physics. The lack of an accurate understanding of nuclear effects hinders these discoveries. Theoretical calculations with quantified uncertainties of neutrino–nucleon and neutrino–nucleus cross sections are essential for progress. Cross sections are needed for a broad set of energies, ranging from the relatively low energies relevant in astrophysical environments to the relatively high energies relevant in long-baseline neutrino oscillation experiments. Studies of the nuclear response in inelastic neutrino scattering benefit from comparisons with the nuclear response measured in electron scattering in comparable kinematics. Furthermore, neutrinos themselves are a tool to uncover the properties of nuclei via scattering experiments (Sidebar 6.3). The following subsections discuss the need for improved measurements of neutrino interactions to support both basic BSM physics searches and to support applications in other fields such as astronomy where neutrinos are used as messengers of information from the cosmos.

6.6.1. Absolute measurements of neutrino mass

Knowledge of the absolute neutrino-mass scale is essential information that would not only provide key input to theoretical models of the neutrino mass but also would reveal, in conjunction with astrophysical observations, neutrinos' role in shaping the large-scale structure of the universe.

The Karlsruhe Tritium Neutrino (KATRIN) experiment in Germany has recently set the world's most restrictive model-independent upper limit on neutrino mass. KATRIN's limit, 0.8 eV, is less than half of the known limit as of the last Long Range Plan. KATRIN will operate through 2025 with significant continued participation of US scientists to collect more data toward its ultimate goal: a sensitivity of 0.2 eV.

The most sensitive way to directly measure neutrino mass is by the tritium endpoint method in which neutrino mass is revealed by its effects on a precisely measured tritium beta-decay spectrum. Any experiment that follows KATRIN will need two new technologies: (1) a scalable electron spectroscopy technique to measure the tritium decay spectrum and (2) a tritium source consisting of atoms rather than the more natural molecular form of this hydrogen isotope. The Project 8 collaboration is developing CRES to answer the former challenge. Planned experiments will show that CRES scales to volumes of at least about 10 m^3 by performing a (molecular) tritium endpoint experiment with neutrino mass sensitivity comparable to KATRIN by about the time of the next Long Range Plan. A parallel effort will demonstrate that large and pure sources of tritium atoms are possible using combined magnetic and gravitational traps, following existing technologies used, for example, to store antihydrogen or UCNs. The ultimate demonstration of the feasibility of Project 8 will be a pilot-scale experiment using both CRES and an atomic-tritium source at the 10 m^3 scale. Project 8 forecasts that a large future phase of the experiment can be sensitive to neutrino masses as low as 0.04 eV, sufficient to measure any mass allowed by the so-called inverted ordering.

Since the last Long Range Plan, the Project 8 collaboration has demonstrated CRES and used it in a prototype neutrino mass measurement. CRES converts an energy measurement into a frequency measurement by detecting the microwave emissions of electrons in a magnetic trap (Figure 6.9). The technique has inherently sharp energy resolution and very low backgrounds. With this approach, Project 8 set a limit on the neutrino mass of 155 eV in a small prototype apparatus with no background events observed.

Tritium is appealing for a neutrino mass measurement because of its very low 18.6 keV beta-decay endpoint energy (more typical beta-decay endpoints are on the order of MeVs). Statistical sensitivity to neutrino mass by the beta-decay endpoint method scales like the inverse cube of the endpoint energy, so lower endpoints are highly advantageous. Therefore, even lower endpoints are sought for future measurements. Additional candidates for ultralow endpoint energy decays (<1 keV) that rely on ground-state to excited-state transitions have been proposed based on literature searches, but a program of precision measurements of the parent and daughter atomic masses, and of specific excitation energy levels, is required to establish whether these candidate transitions are energetically possible. For shortlisted candidates, the next steps would be to observe each specific decay experimentally and then to perform R&D for neutrino-mass experiments. A spectral measurement of beta decay or electron capture can reveal the neutrino mass. Complementary efforts using other isotopes embedded in superconducting sensors, such as holmium-163, are also being explored.

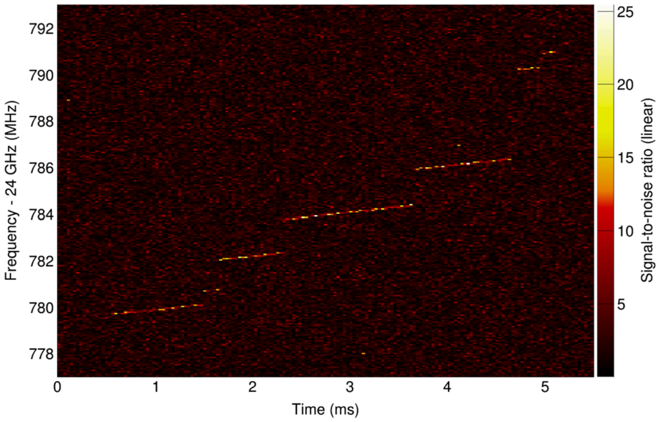


Figure 6.9. The first CRES event ever detected determines the energy of a conversion electron by the frequency (vertical axis) of radiated power (color scale) over time (horizontal axis) [30].

6.6.2. Sterile neutrinos and new light particles

Experiments such as KATRIN and Project 8 can achieve such unprecedented precision that they can also be used to search for new fundamental light particles. Discovery of these new invisible particles would dramatically accelerate our quest for understanding the microscopic nature of cosmology and the connection to the Standard Model. KATRIN has already set leading limits on the existence of light (electronvolt-scale) sterile neutrinos, with future upgrades under development that will see the Tritium Sterile Anti-Neutrino (TRISTAN) detector perform a search for these elusive particles in the few-kiloelectronvolt mass range to a sensitivity level that connects laboratory and cosmological measurements.

Above 10 keV, the Beryllium Electron Capture in Superconducting Tunnel Junctions (BeEST) experiment (Sidebar 6.4) uses electron capture decay of beryllium-7 embedded in state-of-the-art superconducting sensors to provide the most sensitive search for these particles below 1 MeV. Both the BeEST and Heavy Unseen Neutrinos by Total Energy-Momentum Reconstruction (HUNTER; optical trapping of cesium-131) experiments will increase their sensitivity to these particles by several orders of magnitude during the next decade. This class of experiment is an area of strategic development opportunity in nuclear physics, and several searches using quantum sensing technologies are in development.

6.6.3. Neutrino–nucleus scattering

Direct detection of neutrinos is incredibly challenging because of their miniscule interaction probabilities. Given the tremendous importance of understanding these interactions for applications and fundamental science (e.g., astrophysical, reactor, source), continued work in this area is critical.

At lowest energies, neutrinos can undergo coherent elastic neutrino–nucleus scattering (CEvNS) in which a neutrino interacts with a nucleus in such a way that the constituent nucleons recoil in unison. The main experimental challenge for CEvNS detection is the tiny nuclear recoil energies—it is like looking at the scatter of a grain of dust off of a bowling ball and measuring how much the bowling ball recoils. Nevertheless, this interaction was observed for the first time in 2017 by the Coherent Elastic Neutrino–Nucleus Scattering (COHERENT) experiment at a stopped-pion source and has now been observed in cesium iodide and argon. CEvNS at reactors, where neutrino energies are an order of magnitude lower than at stopped-pion sources, has yet to be observed, owing to the severe challenge of sub-kiloelectronvolt nuclear recoil detection, although many experiments are underway. As CEvNS experiments improve in precision, they will provide powerful probes of nuclear electroweak properties, sterile neutrinos, and nonstandard neutrino interactions.

6.6.4. Solar neutrinos

The Sun is a powerful laboratory for the study of nuclear physics. The nuclear reactions that power the Sun produce more neutrinos than any other source—natural or artificial. This power enables precision tests of low-energy nuclear reactions and the interactions of neutrinos. Nuclear physics has been the steward of these studies, including the most recent Nobel Prize in nuclear physics, for the Sudbury Neutrino Observatory (SNO) experiment, which proved that solar neutrinos change flavor on their journey from the Sun and that the Sun's fusion reactions are well understood. This foundational result underpins the neutrino program that is at the heart of major efforts in both nuclear and high-energy physics.

Many critical questions remain. Among these is an unambiguous observation of the predicted behavior from the Mikheyev–Smirnov–Wolfenstein (MSW) effect, which should be manifested in both a difference in the solar electron neutrino flux observed between day and night and in a transition between the neutrino flavor change enhanced by the matter of the Sun at high neutrino energies (>5 MeV), compared with vacuum-only oscillations at low energies (<1 MeV). This transition should occur somewhere between about 1 and 5 MeV. The vacuum/matter transition is particularly sensitive to BSM physics scenarios involving nonstandard neutrino interactions. A measurement of neutrinos emitted in the carbon–nitrogen–oxygen (CNO) fuel cycle more precise than the Borexino experiment has made would also allow a clear discrimination between models of solar core metallicity, with implications for solar system formation (Sidebar 5.1). A precision measurement (at the 1% level) of the proton–proton fusion solar flux (or, possibly the proton–electron–proton flux), would allow a real test of whether the total light output of the Sun matches the energy produced by its burning. Any deviation of the neutrino measurement from the total energy measured by the Sun's photons would indicate either new energy-generation or some kind of energy-loss mechanisms.

6.7 THEORETICAL RESEARCH

Theoretical research is an integral part of the nuclear science endeavor in FSNN. Theory assesses the discovery potential of FSNN experiments and motivates new experimental directions. Through multiscale analyses, theory elucidates how BSM sources of symmetry violation manifest in the hadrons and nuclei used in experiment; it provides the Standard Model predictions for precision tests; and it delineates the broader implications of fundamental symmetry tests and neutrino studies, connecting them with complementary studies at the high-energy and cosmic frontiers.

This chapter discusses recent progress and opportunities for theory in the next decade. The recent progress has drawn on a small core of faculty and laboratory scientists whose research focuses on FSNN. This progress has also depended on collaborative efforts between this core and a wider network of nuclear theorists in other subfields (e.g., lattice QCD, nuclear structure), necessary to tackle multiscale problems, as well as colleagues in high-energy physics, astrophysics, and cosmology.

Full realization of the FSNN scientific opportunities enabled by experimental investments requires growing this core and capitalizing on the synergies with related areas of nuclear theory. As discussed in Chapter 7, "Theoretical Nuclear Physics," this need can be addressed by establishing a national FSNN Theory Consortium to award postdoctoral fellowships and bridge positions at universities and national laboratories. Moreover, because the FSNN community does not have a single dedicated facility, this consortium would also bring together the relevant subfields and stimulate interaction between theory and experiment.

6.8 SUMMARY AND CONCLUSIONS

The study of fundamental symmetries and neutrino properties allows us to tackle some of the deepest questions about the universe. Neutrons and nuclei serve as unique and powerful laboratories to search for new physics across energy scales, probing new phenomena that may exist well above the scales accessed directly by high-energy particle colliders. These measurements require specialized experiments and facilities that harness unique US-based capabilities. The suite of experiments presented in this chapter leverages a wide variety of techniques to push the bounds of what is measurable and calculable and ensure US leadership on the frontier of our understanding of the fundamental physics governing our universe.

7 THEORETICAL NUCLEAR PHYSICS

A vibrant nuclear theory community is crucial to nuclear science. Theory shows how fundamental interactions produce the observed properties of hadrons, nuclei, and dense matter. It traces the implications of those properties for the history of our universe, extreme astrophysical environments, precision tests of the Standard Model, and applications of nuclear science. Theory also motivates, interprets, and contextualizes experiments at national user facilities and university laboratories and can open fresh vistas that lead to new experimental programs.

Since the last Long Range Plan, nuclear theory has made impressive progress in all subfields, as detailed in the science chapters. Headway on lattice QCD calculations on the parton distribution functions (PDFs) for polarized and unpolarized quarks and gluons show transformational potential (Sidebar 3.1). The development of complex cohesive theoretical frameworks connects phenomenology of heavy ion collisions to the properties of the quark–gluon plasma (Sidebar 3.7). Theoretical unification of nuclear structure and reactions for light nuclei provides fundamental and quantitative predictions for Big Bang nucleosynthesis and the fusion program (Chapter 4). Advances in nuclear theory and astrophysical modeling are crucial to the interpretation of multi-messenger signals from the first neutron star merger event observed by the Laser Interferometer Gravitational-Wave Observatory and Virgo interferometer (Chapter 5; Sidebars 5.2, 5.3). Theory benchmarks of many-body methods, from light nuclei to tin, lead to important progress in our understanding of weak decays, solving a long-standing discrepancy between experiment and theory (Chapter 6). While advancing nuclear science in all these fronts, nuclear theory continued to train the workforce in areas of critical national need and forged new important technical innovations that will benefit society (Sidebars 7.1, 7.2). Also, since the last Long Range Plan, our awareness of the challenges surrounding diversity, equity, and inclusion has increased; community agreements and codes of conduct setting expectations for behavior are becoming standard (Institute for Nuclear Theory [INT] and Facility for Rare Isotope Beams Theory Alliance [FRIB-TA]); and conversations on creating an inclusive environment among theorists are becoming more frequent.

Theory is a connective tissue across nuclear physics, and between nuclear physics and other science fields and societal applications. Theory plays this role because it is not tied to a particular facility: theoretical work can move between subfields, offering the broad perspective essential to identify synergies. Although no theory facilities exist, a theory ecosystem relies on a delicate balance of activities distributed across the country at universities and national laboratories. Theory faculty at universities and colleges have the vital responsibility of attracting and educating new scientists, and, together with their theory colleagues at universities, theory staff at national laboratories have an important mission in training and retaining the expert workforce that is critical to the nation. The delocalization of theory activity makes it especially important that there be a healthy infrastructure, enabling theorists to come together, join forces, and tackle the stimulating, important, and challenging problems that define our field.

Theory blossoms in many ways: great ideas can come from small teams with graduate students and postdocs, or the creative spark may need larger collaborations with a diverse set of expertise and backgrounds. Often, discussions with experimental colleagues generate new ways of thinking. The key is to have a balanced program, equitable and welcoming for all, that sustains all these theory-progress drivers.

7.1 THE FOUNDATION: CORE THEORY RESEARCH

The core nuclear theory program as implemented at universities and national laboratories is the mainstay of the entire theory effort. It integrates experimental data obtained in US world-class facilities to develop deep insights into the underlying causes of nuclear phenomena, creating an overall understanding greater than that obtained by theory or experiment alone. It addresses fundamental questions in strongly correlated quantum systems, from nuclei to heated and compressed nuclear matter, spanning a wide range of energies. It addresses electroweak interactions in nuclei and how these may be used to explore physics beyond the Standard Model. It explores how nuclei are created in stars and stellar explosions. And it provides invaluable guidance to experiment, offering the science case for new nuclear physics facilities and experimental campaigns (e.g., FRIB, EIC, ton-scale neutrinoless double beta decay experiments) and the agility to react to new discoveries.

The many achievements of the core nuclear theory program are woven throughout the science chapters. They include (1) a decisive constraint by lattice QCD on the location and nature of an expected QCD phase transition at high temperature and the elucidation of the computational constraints of PDFs and generalized parton distributions (GPDs) of quarks and gluons in high-energy and high-density QCD collisions (Chapter 3); (2) impressive progress on effective field theory methods along with lattice QCD and nuclear structure computations critical to the neutrinoless double beta decay program (Chapter 6); and (3) prediction of the limits of existence of isotopes up to iron, using density functional theory with uncertainty quantification, to be tested at FRIB (Chapter 4).

The optimum operation of the core nuclear theory program, and indeed the entire nuclear physics enterprise, requires a diverse theory community with multiple perspectives, interests, and backgrounds. Small teams at universities are critical for recruiting new scientists into the field, and theory groups at both national laboratories and universities nurture these early career scientists into a cohesive workforce connected to the large-scale national experimental facilities and computational programs. Strong support for both the permanent and early career workforce is essential for a successful operation. Specific examples are provided in Sidebar 7.1.

Nuclear theory ties together all components of nuclear physics described in the science chapters, elevating nuclear physics in the overall national physics program. Efforts spanning several research areas are often initiated in the core research program, enabling maximum impact across multiple fields. Two examples are the studies of how the physics of nuclei and nucleonic matter manifest in multi-messenger observations of core-collapse supernovae and neutron star mergers (Chapter 5) and the research on how electron and neutrino scattering from nuclei can help probe neutrino properties and physics beyond the Standard Model (Chapter 6). Typically, initial efforts are fostered by the core research program and can evolve into focused efforts with larger collaborations.

Theory continues to be a driving force in technical developments: artificial intelligence (AI) and machine learning (ML) tools are being creatively used to advance the entire program, and theory contributions

Sidebar 7.1 FRIB Theory Alliance: A Successful Paradigm

Connecting QCD, the fundamental theory of the strong interactions, with the unique phenomena that emerge in atomic nuclei is at the core of the research program pursued by the early career faculty supported by the FRIB theory alliance (FRIB-TA). This talented group of scientists are investigating simple patterns that emerge in nuclei from the complex many-body dynamics; making precise and accurate tests of the Standard Model by identifying how these nuclei interact with the elusive neutrino; understanding the role of the continuum in the most exotic nuclei at the limit of their existence; and studying the structure of neutron stars and their binary mergers. These efforts transcend the boundaries of traditional nuclear physics by building connections to high-energy physics, neutrino physics, and gravitational-wave astronomy.

Figure 1. Through the FRIB-TA bridge program five new faculty, developing exceptional theoretical research relevant to rare isotope science, are energizing nuclear groups across the country and two FRIB theory fellows have become staff at national laboratories and are now contribute to national security [S53].

to quantum computing problems are paving the way toward complete knowledge of the structure and dynamics of QCD and nuclei. As in other cases, many new opportunities for nuclear physics in AI/ML and quantum information science and technology (QIST) grew out of research initiated by the core theory research program (Sidebar 7.2).

The highest priority of this Long Range Plan is to capitalize on the extraordinary opportunities for scientific discovery made possible by recent investments. Included in that recommendation is increasing the research budget that advances the science program through support of theoretical and experimental research across the country, thereby expanding discovery potential, technological innovation, and workforce development to the benefit of society.

7.2 BRINGING NUCLEAR THEORISTS TOGETHER

In addition to fostering a strong core research program for advancing nuclear science, we must create opportunities for nuclear theorists to work together and take on complex problems by combining their diverse skills. Collaborative nuclear theory initiatives, such as topical collaborations, encourage theorists to focus on key nuclear physics problems for an established limited time. Although these efforts rely on well-defined pathways to solutions built on theory insights from the core program, they are a powerful mechanism to accelerate progress.

Since the last Long Range Plan, two rounds of awards for US DOE topical collaborations were granted. They have fostered collaborations across traditionally distinct subfields of nuclear theory to address exciting opportunities. They have addressed a wide range of challenging topics that would not have been tackled by a small group and provided much-needed theoret-

Following in the footsteps of the Jefferson Lab bridge program, the RIKEN-BNL center, and the INT fellows, the FRIB-TA was identified as one of the highest priorities for new investments in nuclear theory in the 2015 LRP. This initiative capitalized on the large investment in the experimental facility by establishing a national theory fellow program and creating permanent positions in nuclear theory across the United States in what is now known as the FRIB-TA bridge program.

Besides being involved in cutting-edge research, the FRIB-TA bridge faculty, who have already received several prestigious awards, leverage resources in high-performance computing and develop novel machine learning techniques for uncertainty quantification. These capabilities place them at the forefront of all forms of advanced computing, including machine learning, artificial intelligence, and quantum information science.

Together with the DOE theory topical collaborations, the FRIB-TA fellow and bridge programs have helped address theory workforce shortages in critical areas and fulfill the needs of the nation's overall low-energy nuclear physics experimental program. This successful model can serve as a template for new initiatives as the nuclear physics community develops precision experiments to probe physics beyond the Standard Model, moves toward building an Electron–Ion Collider, and prepares to capitalize on the new era of quantum computers.

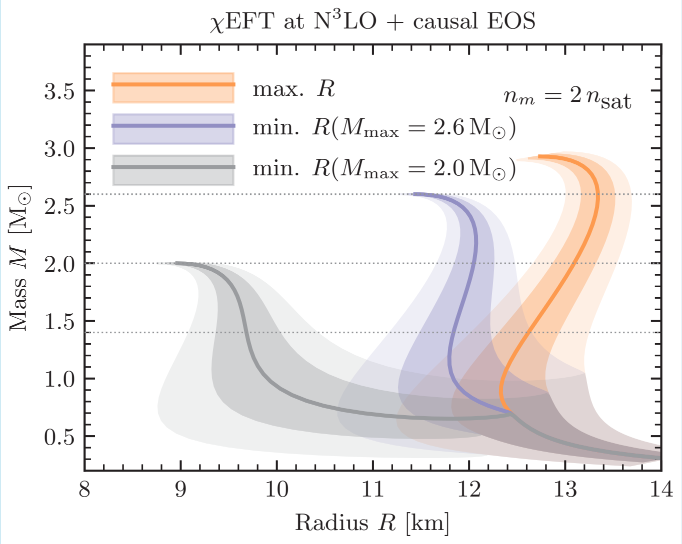


Figure 2. As an example of outstanding research being developed by the FRIB-TA career talent, Drischler and collaborators obtained bounds of neutron-star radii by combining state-of-the-art chiral effective field theory and uncertainty estimation with recent maximum-mass information [S54].

ical support to experimental nuclear physics. They also prepare early career theorists to work effectively in teams. The collaborations selected for funding in 2016 benefited research on hadron structure in QCD (TMD collaboration), double beta decay and fundamental symmetries (DBD collaboration), the phase structure of QCD (BEST collaboration), and fission recycling in the r-process (FIRE collaboration). They have created networks of sustained interactions through schools, workshops, and collaboration meetings and have energized students and postdocs. The latest round of topical collaboration awards from 2022 will enhance theory on neutrino–nucleus interactions and explore new physics beyond the Standard Model in nuclei (NTNP collaboration); advance heavy-flavor theory for QCD matter (HEFTY collaboration); expand the studies of the mass, spin, and tomography of quark–gluon hadron structure to 3D (QGT collaboration); study the saturated glue in QCD (SURGE collaboration); and coordinate efforts on the study of exotic hadrons (ExoHad collaboration).

In addition to collaborations, the INT, through community-driven workshops and programs covering the whole of nuclear science, has helped germinate theoretical methods and concepts and build bridges to other disciplines. The INT provides a unique environment for community organization and planning, facilitating a timely response to emerging opportunities. One excellent example of its important role since the last Long Range Plan is the 2017 INT Workshop on Quantum Computing for Nuclear Physics that has spawned a vibrant research area at the interface of quantum information science and nuclear physics and led to the creation of the InQubator for Quantum Simulation (IQuS; more detail in Chapter 10).

FRIB-TA, a national effort born out of the last Long Range Plan, has introduced interdisciplinary summer schools to expand the impact of FRIB science and topical programs to address nuclear theory problems relevant to FRIB and nuclear data evaluation. Given the success of the FRIB-TA, a similar model may be followed in support of the future EIC facility. The goal of this national EIC Theory Alliance is to support and steward the theory effort in EIC physics. It is discussed in more detail in Chapter 3.4, with emphasis on its role in growing the nuclear physics workforce.

The health of the nuclear physics community depends on the support of effective collaborative, connective activities to tackle the challenges at the forefront of nuclear science. Many of these challenges involve multiscale physics. Enhancement of the DOE topical collaborations program is necessary to realize the full research scope of each collaboration within the preestablished 5 year timeline.

7.3 CONNECTING ACROSS FIELDS AND DISCIPLINES

Nuclear theory plays a multifaceted role in a broad sweep of disciplines, encompassing both applied science and fundamental research. Nuclear theory is a crucial component of the nuclear data program and benefits society through its inputs to applications as diverse as nuclear medicine, space flight safety, and fusion energy. It is also an important player in QIST and has overlapping interests with AI/ML, statistics, and data science (e.g., in the context of uncertainty quantification [Sidebar 3.7]). Nuclear theory is intertwined with particle physics in searches for physics beyond the Standard Model because it guides the interpretation of low-energy experimental results. It bears fruit in problems as diverse as whether the neutrino is its own antiparticle, on why we see more matter than antimatter in the universe, and in the hunt for dark matter using scattering from nuclei. Just as with nuclear theory, theoretical atomic and condensed-matter physics and chemistry also address systems of strongly correlated fermions, leading to a fertile exchange of ideas and methods between these fields. Finally, nuclear theory is pervasive to the history of the universe, key not only to accounting for the element abundances in stars but also to the interpretation of observations of a wide range of astrophysical events such as supernovae and compact object mergers.

Many of these theoretical studies stretch the limits of current computational and algorithmic capacities, driving the expansion of high-performance computing (HPC), and require close collaboration with computer science and applied mathematics. Great examples are lattice QCD—a field that can only exist because of HPC—the complexity of the theory of nuclei, and that of multiscale models of a star's life and death. Because much of the field is organized by facilities, the cross-cutting interdisciplinary work flourishes in centers across disciplines, providing unique holistic training for a multifaceted workforce that ensures a bright future for nuclear science. The NSF Physics Frontiers Centers and Focused Research Hubs have accomplished this goal by bringing together diverse communities of nuclear theorists and connecting them with astrophysicists and observers. DOE's SciDAC program and NSF's Cyberinfrastructure for Sustained Scientific Innovation program have fulfilled this role for computational science and statistics (Sidebar 7.2). IQuS is achieving this goal in connection with quantum information science. The synergies created in these efforts advance other fields and accelerate nuclear theory.

Advanced computing has been identified as a strategic opportunity (Chapter 1). As we enter the era of exascale computing—when an increasing number of communities in nuclear physics are poised to take advantage of HPC—enhanced support to the SciDAC program would be required to maximize scientific progress.

7.4 GROWING THE WORKFORCE

A robust nuclear theory workforce is essential to realize the full scope of the nuclear theory programs and develop new connections and ideas for future research directions. Equally important is the growing industry need for a theoretically trained workforce that is equipped with a wide range of skills, including big data and AI/ML. Currently, the theoretical nuclear physics workforce is grown through a few mechanisms in addition to the standard mechanisms at national laboratories and universities. The INT grows the nuclear theory workforce through its postdoctoral and fellow programs, training future leaders in a uniquely stimulating environment; topical collaborations leverage university support to create bridge positions, contributing to the whole nuclear theory effort (nine new faculty positions are expected from the 2022 topical collaboration selection); and the FRIB-TA, leveraging university and national laboratory support, enhances the FRIB theory research through its fellow program and its bridge program. These mechanisms have been extremely successful: fellows have moved to permanent positions, and bridge faculty successfully advance and secure funding through early career awards.

The recently created IQuS is training nuclear theorists working at the interface with QIST, through postdoctoral and research assistant professor positions. The Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS) is training a new generation of theory postdocs at the intersection of nuclear physics, astrophysics, and cosmology.

In the future, theory will continue to be key in extracting the science from data obtained from the large US investments in new accelerators and detectors. As we prepare for the challenges ahead, remaining theory workforce gaps must be addressed with new strategic initiatives.

Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) Theory Consortium: The growing scope of experimental activities associated with tests of fundamental symmetries in nuclei urgently needs a concomitant increase in the relevant theory. Currently, the FSNN theory support is subcritical. Understanding the signatures of new fundamental interactions in hadrons and nuclei needs diverse expertise at the interface of nuclear/hadronic structure and dynamics and the phenomenology of fundamental interactions within and beyond the Standard Model (Chapter 6). A national consortium facilitating postdoctoral fellowships and bridge positions at universities and national laboratories would address this need. Because the FSNN community does not have a dedicated facility, this consortium would serve as an FSNN-dedicated theory group at a major national laboratory.

Recommendation 2 of this Long Range Plan includes the statement that **an enhanced theoretical effort in fundamental symmetries is essential to elucidate the underlying physics of any neutrinoless double beta decay signal; such an effort is an integral component of the neutrinoless double beta decay campaign.**

EIC Theory Alliance: Theory is key in the study of multidimensional partonic structure and gluon saturation, the central goals of the EIC program. The scope of theory for the EIC encompasses many areas from formal theory, quantum information science, phenomenology, global analysis, exascale computing, and AI/ML. A timely investment in an EIC theory alliance, unifying these research areas, creating theory fellow and bridge permanent positions at universities to allow for graduate student training, expanding the efforts on EIC theory beyond national laboratories, would accelerate the pace of discovery (Chapter 3.4).

Recommendation 3 of this Long Range Plan includes the statement that, **to achieve the scientific goals of the EIC, we recommend an investment in QCD theory in parallel with the facility construction. Progress in theory and computing has already helped drive and refine the physics program of the EIC. To maximize the scientific impact of the facility, theory must continue to advance on multiple fronts, requiring new collaborative efforts to prepare to confront the precise data from the EIC.**

Nuclear Physics Quantum Connection: A diverse and sustainable quantum-ready workforce is crucial for both the nuclear physics and QIST communities. Recruiting and training this new generation of researchers will accelerate the development and integration of quantum technologies in nuclear physics research. Establishing a Nuclear Physics Quantum Connection will achieve the transformational potential of QIST in addressing nuclear physics grand challenges (Chapter 10) and was identified as a strategic opportunity by the nuclear science community (see Chapter 1).

All these initiatives offer a timely opportunity to grow and diversify the theory workforce while creating and sustaining an equitable, welcoming, and inclusive culture.

Sidebar 7.2 How Nuclear Theory Fosters Innovation

The nuclear theory ecosystem functions holistically to guide and support experimental programs, develop the theoretical and computational directions of the future, and communicate and integrate new results with other science and technology domains. It also provides invaluable workforce to critical areas of the US economy. Universities and national laboratories are the engines that drive us toward these intertwined short-, medium-, and long-term goals. The last decade has seen several advances that have sprouted in small local research groups, flourishing there until the ideas and methods could be widely adopted and incorporated into the priorities of larger parts of the ecosystem. Here we discuss two representative examples.

[S55]

Full quantification of uncertainties in predictions
Around the time of the last LRP, several researchers in university and laboratory groups began using data-intensive Bayesian statistical methods to systematically include nuclear physics model uncertainties in predictions and in parameter inference. The resulting methods have improved our ability to compare theory with experiment in all subfields of nuclear science. One science application is the Bayesian analysis of the transport particles of dense nuclear matter. These methods are now part of the toolkit employed in many larger efforts (e.g., topical collaborations) and are being disseminated through multi-institutional collaborations such as the Bayesian Analysis of Nuclear Dynamics Cyberinfrastructure for Sustained Scientific Innovation (CSSI) software framework. The ability to better fit and compare theory with data is also beneficial to the nuclear data enterprise. Because research in this area involves data analysis and machine learning tools, students working on these projects have proven highly employable beyond nuclear physics, proceeding, for example, to careers in quantum computing, to data-driven activities in other research fields such as medical science, and throughout the private sector.

Quantum information science and technology and quantum computing

This new area emerged since the last LRP as a high priority for US research. Nuclear theorists have expertise and techniques that solve highly correlated and strongly interacting quantum many-body problems. These assets are valuable for quantum information science and technology (QIST) research. And this relationship is symbiotic: these areas of nuclear theory are being advanced because of developments in QIST. Quantum algorithms and circuits specific to solving problems unique to nuclear physics are co-designed with evolving quantum hardware in partnerships among universities, national laboratories, and technology companies. These algorithms and circuits, together with sophisticated entanglement tools developed for QIST, are leading to new pathways to solve key nuclear-theory problems: pathways that can produce more accurate and faster solutions. The theory activity in this emerging area thus helps meet the Nation's 21st-century need for a skilled quantum workforce. As in the other example discussed here–and those that are not discussed–these developments began in small research groups and are now being accelerated through mechanisms such as the Incubator for Quantum Simulation.

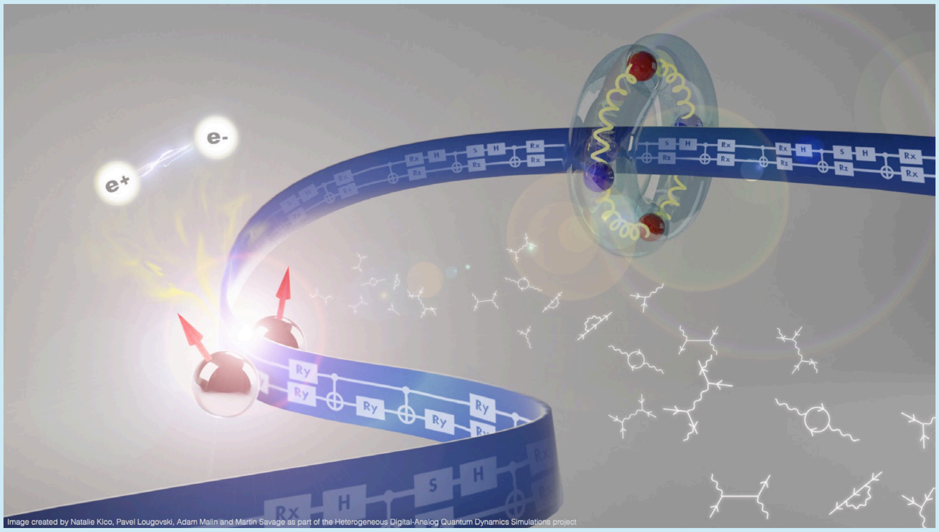


Image created by Natalie Klco, Pavel Lougovski, Adam Malin and Martin Savage as part of the Heterogeneous Digital-Analog Quantum Dynamics Simulations project

[S56]

8 DEVELOPING A NUCLEAR WORKFORCE FOR THE BENEFIT OF SOCIETY

8.1 INTRODUCTION

People are central to the scientific enterprise. A discussion of the compelling nuclear science for the next decade must inherently include a discussion of the people—at every level—who will pursue that science and the skills and societal applications that spring from it.

A skilled nuclear science workforce contributes substantially to US innovation and economic growth, including the development of new machine learning tools for finance, the careful and state-of-the-art treatment of cancer patients, and the education of the next generation (Sidebars 8.1 and 2.1 highlight some of these individuals). However, the number of people currently being trained and educated in nuclear science is insufficient to meet the workforce needs of academia and research laboratories, industry, and other sectors, including advanced nuclear power in the US, which estimates growth of 100 thousand skilled jobs by 2050. The community must work to attract, train, and retain highly qualified persons from all groups, including those who have been historically underserved in nuclear science, including from minority serving institutions, non-R1 institutions of higher education, and institutions of higher education in Established Program to Stimulate Competitive Research (EPSCoR) participating states. To fulfill our science mission and provide a highly qualified workforce for societal needs, we must ensure that education in nuclear science begins at a young age and continues through all stages of a student's career. We must reach out to educate the public, including parents, teachers, and lawmakers. The ability to attract, grow, and sustain a national nuclear workforce also depends on our community's commitment to equal opportunity and a respectful working environment, which are necessary to draw on the talents of the entire nation. The highest recommendation of this Long Range Plan includes two key aspects of workforce development and retention:

- Raising the compensation of graduate researchers to levels commensurate with their cost of living—without contraction of the workforce—lowering barriers and expanding opportunities in STEM for all, and so boosting national competitiveness.
- Expanding policy and resources to ensure a safe and respectful environment for everyone, realizing the full potential of the US nuclear workforce.

These components assist in removing barriers to full workforce participation, enabling institutions and workplaces to become supportive and inclusive, naturally promoting intellectual curiosity, engagement, and equal opportunity. Ultimately, the success of nuclear science and its contributions to our national goals relies on the ability to attract and retain a talented workforce, as well as a durable pipeline for sustaining it.

8.2 COMPELLING QUESTIONS AND CHALLENGES IN DEVELOPING THE NUCLEAR SCIENCE WORKFORCE

PhD-trained nuclear scientists are highly desirable for employment in academia and fundamental research, national laboratories, corporations, governmental organizations, and federally funded research and development centers. This workforce drives the exciting science elaborated in this Long Range Plan. The challenge for the community is to grow the available workforce while providing the unique hands-on training that makes that workforce critical to the scientific enterprise. To achieve this goal, a wide range of efforts is needed, including improved communication with the public, recruitment of students from all areas of society, increases in hiring at the assistant and associate professor levels, recognition of the importance of work-life balance, and a more inclusive and supportive workplace culture.

With the increasing demand for a workforce versatile in a wide range of hardware and software skills (such as big data, artificial intelligence, machine learning, quantum computing, cryogenics, or microelectronics), acquired by students in nuclear science, an increasing number of doctoral graduates are recruited by for-profit and nonprofit corporations. Figure 8.1 tracks a group of students for 5 to 10 years, demonstrating the skills used in these positions. The number of doctoral graduates in nuclear science has increased from about 80 per year before 2014 to around 100 per year since then, but it has not been sufficient to keep up with the increased workforce demands. Several factors can help explain the stagnation in the size of the nuclear workforce: barriers to education, a faculty shortage, public perception, and financial and sociological barriers to full societal participation.

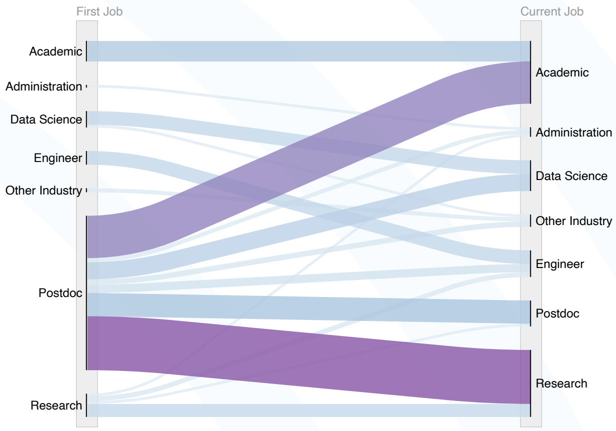


Figure 8.1. Where have students graduating from programs in nuclear physics ended up? *Scientists reported on their first position after obtaining their doctorate (left side of the plot) and their current position, 5–10 years post-PhD (right side of the plot). Nuclear science graduates can be found in research (both basic and applied), engineering, program administration such as at governmental agencies, and even data science. The skills learned in the field translate well to other technical positions [31].*

Nuclear science and engineering are highly technical fields, requiring significant education and training. Barriers to education and training in this field may prevent some potential candidates from pursuing careers in nuclear science. Meanwhile, the drop in early career faculty recruitment of those qualified to teach nuclear science (as shown in Figure 8.2) leads to a reduction in available expertise, a decrease in research output, difficulty attracting and retaining students, and a decrease in the quality of nuclear education.

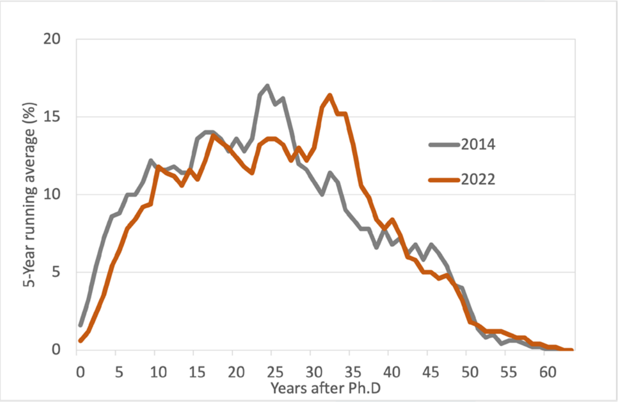


Figure 8.2. Percentages of nuclear physics faculty for a given time since PhD, compiled for the current and previous Long Range Plan. *The y-axis is a 5-year average. A shift upward in the average years past PhD indicates an aging workforce [32].*

Physics stands out as one field that does not represent the demographics of the United States and continues to be less diverse than other STEM fields. The lack of diversity among physicists is an ongoing problem and, while it persists, physics—and nuclear science—will fail to achieve its full potential. Ensuring equality of opportunity in physics is imperative to increase productivity and potential for new discoveries by engaging new viewpoints while making available a broader pool of talent.

In physics, women earn fewer than 20% of doctorates, with about 21% of master's degrees, and about 23% of bachelor's degrees awarded to women in 2020. For comparison, the percentage of women obtaining doctorates in all fields in the same time period was closer to 50%. Black Americans[1] have experienced the smallest gain in physics representation in recent years. Whereas bachelor's degrees increased by 43% in all academic fields for Black Americans from 2005 to 2015, that number only increased by 4% in physics. This number is minuscule when physics degrees increased by 57% for all students during that period. For the classes of 2018 and 2019, Black Americans represented only 1% of the physics doctorates, and Hispanic Americans accounted for 4%.

Comparing nuclear physics faculty numbers in the United States demonstrates some meaningful trends. Figure 8.3 shows that the percentage of faculty members being trained at US institutions is shrinking; we are relying more on doctorates produced internationally. The decrease, or stagnation, in the number of permanent staff at US national laboratories, as shown in Figure 8.4, is also concerning. Although data prior to 2014 are not included in the figure, this number is the lowest it has been since 2009.

The nuclear science enterprise faces a challenge: how to recruit, train, grow, and retain the workforce needed to enable a new decade of scientific discovery and societal applications. Meeting this challenge requires a broad, multipronged approach across the nuclear physics community, addressing many aspects of workforce development. The number of entering university faculty must grow to provide the necessary training to prepare for a hands-on, STEM-ready education. This education needs respectful, engaging, and supportive work environments. Most of all, the workforce needs the support to take on this challenge in the coming decade and beyond, both in policy and resources.

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[1] All degree statistics which include ethnic and race statistics are for US Citizens and Permanent residents only with definitions defined by the US Department of Education.

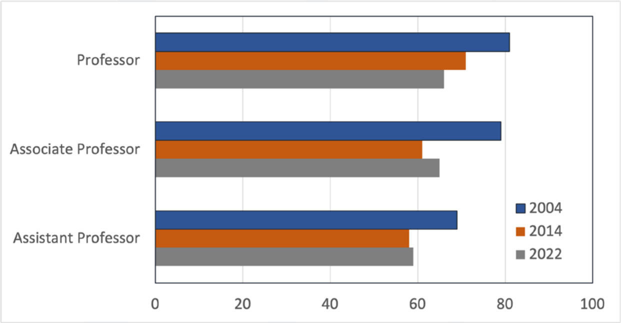


Figure 8.3. Percentage of nuclear physics PhD faculty trained in the United States. *Since 2004, the numbers have dropped [33].*

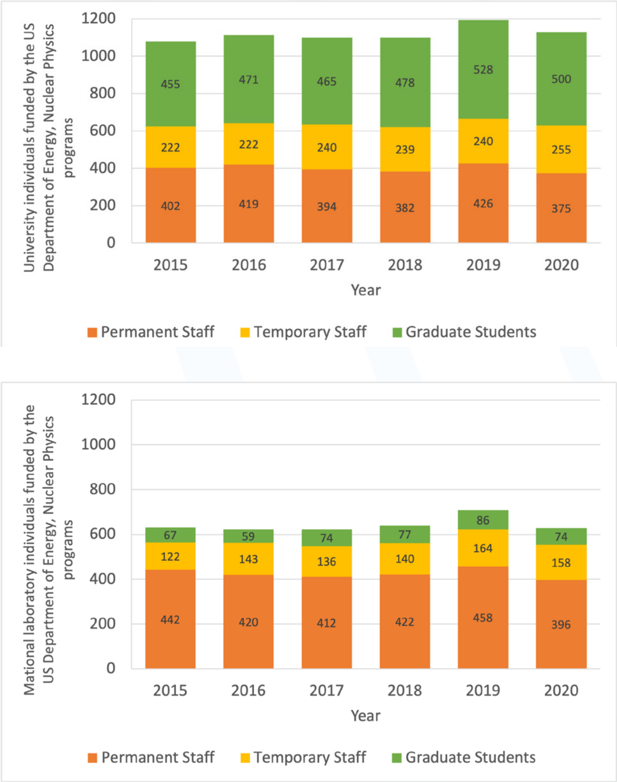


Figure 8.4. Scientific workforce funded by the US Department of Energy, Nuclear Physics programs at universities (top) and national laboratories (bottom) [34]. *(Note: The US Department of Energy Isotope Program was created and removed from the Nuclear Physics Program in 2019, accounting for the reduction in permanent staff positions.)*

8.3 EDUCATING THE PUBLIC IN SCIENTIFIC LITERACY

Engaging the public in the excitement and importance of nuclear science, and STEM in general, is a critical step. Doing so expands and enhances the pool of future scientific leaders and enables meaningful discussion of the excellent return on investment that the nuclear science enterprise represents. Nuclear physics is about the study of matter in all its forms, touching on the smallest constituents of our universe—subatomic particles—to some of the largest—massive stars, supernovae, and neutron star mergers. All four of the fundamental forces of nature—gravitational, electromagnetic, weak, and strong—are present in nuclear physics. Nuclear scientists have made and continue to make many discoveries, which not only advance our understanding of nature but also enable new technological breakthroughs and innovations, leading to applications with broad societal benefits. The ramifications of nuclear science can be felt in basic research and in nuclear medicine, nuclear energy, detection of illicit cargo material, oil well drilling, and even in-home smoke detectors. Nuclear science produces highly sought-after trainees in many sectors, including banking, data science, and medical research. This message is powerful and compelling: nuclear science contributes substantially to the nation and the world.

A large percentage of outreach has been performed by individual institutions and scientists as part of their local communities. For example, FRIB hosts laboratory tours, art shows, and local talks for a general audience. Jefferson Lab hosted a Teacher Night for elementary and middle school teachers. A recent Open House at Argonne featured popular tours and hands-on demonstrations in the Argonne Tandem Linac Accelerator System facility. Many ARUNA laboratories, sited at university campuses, regularly host events for the public. Figure 8.5 shows some of these events.

Figure 8.5. Laboratory open houses and outreach events can reach a wide audience and engage them in learning about the tools and applications of nuclear science [35].

Additionally, scientists have engaged through professional societies, user facility groups, and other associations. Many have organized public lectures and informal events, such as "physics on tap," to reach out to a variety of local communities during conferences. Proactively working with communication staff at institutions to translate results into news releases, funding agency science highlights, popular science articles, or pieces in local newspapers and/or online news outlets, helps disseminate these exciting results to broad audiences. The nuclear physics community can follow the successful practice of the astronomy community to make data available in forms that the public can explore for fun and learning.

The social media landscape has grown explosively since the last Long Range Plan, but that growth has been distributed across many platforms. As a result, somewhat piecemeal efforts of many individual nuclear physicists have thus far been required to provide content about current nuclear physics research via each of these platforms and to a wide variety of audiences of different ages and backgrounds with science. `Quantum 3` is an educational game played on a mobile device. *My Nuclear Life* is a podcast discussing the intersection of nuclear science and society. A Jefferson Lab–Massachusetts Institute of Technology collaboration has produced visualizations of the quark and gluon structures and made them accessible on globally available social media.

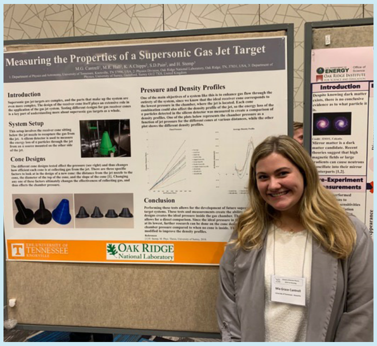
According to a recent American Physical Society poll, nearly 70% of members reported having facilitated or led a public engagement activity. Similar-

Sidebar 8.1 Reducing Barriers for Appalachian Students

Students in nuclear science use their skills to pursue careers not only in nuclear science but also in other sciences, private industry, and government.

Mia Grace Cantrell participated in the Appalachian Students Promoting the Integration of Research in Education (ASPIRE) scholarship program. ASPIRE aims to introduce students from 52 Appalachian counties to research at the University of Tennessee, Knoxville, in particular those who are first-generation college students or who are from economically distressed regions. The program was more than just financial support, Mia Grace noted: in addition, it “served as support through my time in transition from high school to college during my freshman year, helped me get involved with an undergraduate research lab, and guided me with my graduate school applications my senior year.” The program funded her to participate in a summer research internship and to present that research in several national venues. “My experiences in research have absolutely impacted where I am today,” she explained. She is now in graduate school where she studies the cell movement critical to healing wounds.

The detailed classwork and lab experience gained by physics undergraduates at West Virginia Wesleyan College have helped teach nuclear science to myriad students in West Virginia. Graduates from WVWC have gone on to roles in nuclear science across the United States, including James Abraham, a radiation safety officer for Colorado State University; Jason Martin, a lecturer at the Naval Nuclear School in Charleston; and Tom Damiani, who designs nuclear propulsion systems for the Navy.



Mia Grace presented her undergraduate research as part of the Conference Experience for Undergraduate program at the Division of Nuclear Physics annual meeting in Crystal City, Virginia, in 2019 [S57].

[S58]

Students and staff at WVWC [S59].

ly, physicists stated that it is important for them to engage with the public. However, they noted some barriers to engagement. For example, members of underrepresented groups are more likely to need additional financial resources to conduct their public engagement activities. Also, many nuclear physicists have job demands that prioritize research, teaching, and service to their institution over public outreach. Finding a balance that works for everyone takes an investment of time and effort, and many who wish to do more outreach realize that they are unable because of their other duties.

The nuclear science enterprise is thus likely to benefit significantly from a more collaborative and organized effort to engage the public. **Coordinating outreach efforts across the field of nuclear science (e.g., as is done by space science through NASA), will share best practices and new ideas, reduce the overhead required to develop and adopt new outreach tools, reach out to established science communications, and enable a more unified message as to the importance of nuclear physics research.**

8.4 INTRODUCING PRECOLLEGE STUDENTS TO NUCLEAR SCIENCE

Exploiting the enormous scientific opportunities and addressing the critical needs of society requires equal opportunity for all to aspire to a career in nuclear science. An interest in science develops early in a child's life. The nuclear community can encourage this interest with efforts to make the subject accessible, engaging, and fun. For example, although girls and boys have similar math performances in their primary and secondary education, girls lose interest in STEM much earlier than boys do. Effective strategies to keep them engaged include employing active learning exercises and sharing the societal impact of STEM as an integral part of classroom learning. Such strategies make these fields more attractive to everyone but especially to girls, boys who are members of underrepresented groups, and first-generation college students.

Week-long Nuclear Medicine and Science Summer Camps are an example of an engaging activity that might prompt a young person to consider a career in nuclear science. These camps for middle school students are held at Florida State University (FSU) and at TAMU. They are free to families and are led by community teachers who engage in hands-on activities using nuclear detectors. The involvement of community teachers is important because the most effective informal STEM educational experiences involve buy-in from individuals who play important roles in students' lives, such as parents and teachers. The societal impact is communicated through lectures and visits to local nuclear-medicine facilities. Other trusted organizations include the Boy Scouts and Girl Scouts of America. The Girl Scouts Chicagoland Council and the American Nuclear Society developed a Nuclear Badge for the region, and the Boy Scouts have a nationally available Nuclear Science merit badge.

Other laboratories host summer activities for precollege students. The Physics of Atomic Nuclei residential summer program for high school students has recently been supported by the Joint Institute for Nuclear Astrophysics Center for the Evolution of the Elements at Michigan State University and, until 2019, the University of Notre Dame. This summer program has competitive admission and attracts applicants from wide geographic regions but can currently accept only 20% of applicants.

These programs educating precollege students are important whether the students pursue nuclear science careers or not. Students who have learned about nuclear science, and the good it can do in society, will be more informed citizens, and the math skills and scientific reasoning introduced in the programs will transfer to other STEM fields.

8.5 UNDERGRADUATE EDUCATION AND RESEARCH

Undergraduate research opportunities in nuclear physics serve as the community's most effective recruiting and teaching tool. These programs can occur at national laboratories through DOE-sponsored programs such as Summer Undergraduate Laboratory Internships (SULI), as well as at universities, both through NSF-sponsored Research Experience for Undergraduates (REU) programs, university initiatives, the DOE Traineeship program, and individual investigator grants. These experiences allow students to spend the summer working on cutting-edge research programs with scientists while being paid for their work, alleviating the need for alternative summer employment.

The Conference Experience for Undergraduates (CEU) program, now in its 26th year, has provided a capstone conference experience for undergraduate students who have conducted research in nuclear science by providing them the opportunity to present their research, explore the field of nuclear science research (including a graduate school fair), and meet the community at the annual fall meeting of the American Physical Society Division of Nuclear Physics. In a survey of the last 10 years of CEU alumni with 929 respondents, 17% of CEU students have already earned a doctorate, 16% have other advanced degrees, and 42% are currently attending graduate school. An impressive 90% of these students are working in a STEM field and are contributing to the US technical workforce.

On average, nuclear physics accounted for 5% of all physics doctorates awarded (2015–2021), as shown in Figure 8.6. However, among students who participated in the CEU program, this number increased to 42%, showing that nuclear science undergraduate research creates a pipeline to nuclear physics doctorates.

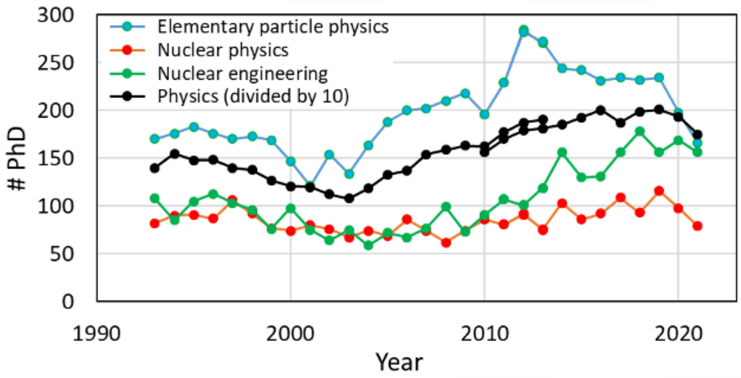


Figure 8.6. ***The number of PhD students in nuclear physics compared to related fields and physics overall.*** *The double black line is an artifact from the merging of two datasets [36].*

Partially in response to the American Institute of Physics Task Force to Elevate African American Representation in Undergraduate Physics and Astronomy (TEAM-UP) report, the DOE NP program created the Traineeships program—now known as Reaching a New Energy Sciences Workforce (RENEW)—which aims to enhance a sense of belonging among undergraduate participants through extended-duration traineeships in partnership with minority-serving institutions. The RENEW program was developed based on the success of the DOE NP Traineeships program (Sidebar 12.1). Early results indicate that the Traineeships program is providing pathways into continuing STEM engagement: about 50% of the 2021 participating seniors now attend graduate school. These programs and similar university and NSF initiatives have enabled the 2022 CEU program to record the highest numbers of Black and Hispanic American student representation since it began keeping statistics. The CEU program has also recorded an increase in the number of women who participate: a high of 45% was reported in 2020. **Funding for undergraduate research programs, including initiatives to remove barriers to entry for students, will continue to increase student interest in nuclear science and bring more students into the field, providing a high return on investment.**

Not all students are exposed to nuclear physics research early in their career. Around 45% of physics students chose to pursue their undergraduate degrees at smaller colleges and universities (non-R1s). These institutions are less likely to have a faculty member familiar with nuclear science; therefore, they are not likely to offer a dedicated nuclear physics course. Consequently, fewer students are exposed to nuclear science as undergraduates, making research experiences an even more important tool for gathering people into the pipeline. Programs such as the Nuclear Science Summer School (NS3) at Michigan State University attempt to address this deficit, but additional work is needed to keep pace with the broad demand.

8.6 GRADUATE AND POSTDOCTORAL EDUCATION AND TRAINING

Graduate school provides advanced education in physics with a specialty in nuclear science. As graduate students, future members of the nuclear workforce start acquiring the skills, education, and habits of mind they will use in their careers. Although these skills are initially developed in the service of nuclear physics research, they are eminently transferable. Earning a doctorate equips today's graduate students to be tomorrow's leaders of the technical workforce.

Nationally, 667 students received a doctorate in *nuclear* physics during the past seven years (out of the 13,494 total physics doctorate degrees granted). In the time spent on the advanced degree, they learned to exercise independence as they took full ownership of a problem in nuclear physics and delved deeply into its solution. In the process, they solved problems that have never been solved before.

To solve these problems, nuclear science doctoral candidates routinely address challenges in instrumentation, modeling, software development, communication, and project management. They develop many skills, including the ability to apply machine learning and artificial intelligence to specific problems; expertise in simulation software applied in fields from space technology to radiotherapy; and designing and installing detectors and readout devices that are used in many technical and industrial engineering fields.

No one institution can offer cutting-edge instruction on all foundational and frontier topics within the field with high frequency, and many are challenged to offer even a basic complement of graduate classes. Students and early career researchers in smaller groups are particularly affected and thus are exposed to only part of the full spectrum of ideas in nuclear physics. The community has begun to address this shortfall with a set of educational initiatives to advance education within the field. The National Nuclear Physics Summer School provides a general overview of nuclear physics while facilitating interactions among experimental and theoretical students in all subfields of nuclear science. The Exotic Beam Summer School rotates around ARUNA universities and several national laboratories to provide a unique mix of lectures and hands-on activities for students and postdocs interested in opportunities with rare-isotope beams (Sidebar 8.2). The Training in Advanced Low Energy Nuclear Theory (TALENT) initiative has developed a broad curriculum of summer school courses, providing cutting-edge theory for understanding nuclei, their reactions, and their application to astrophysics.

Nuclear science doctoral graduates are thus technically skilled, independent problem solvers, who make key contributions to the nation's scientific prowess in a wide variety of areas and in both the publicly-funded and private spheres. Nuclear science doctoral graduates have gone on to careers in everything from academia to banking (Sidebar 2.1).

During the last seven years, the majority of nuclear-science doctoral graduates opted for and received further training—beyond their degree—as scientific researchers, through jobs as postdocs, as shown in Figure 8.7. This career phase is akin to medical residency: a period of mentored development during which scientists deepen their knowledge and skills and gain expertise in managing research projects. Postdocs also serve a valuable role as mentors of undergraduate and graduate students.

Time as a postdoc is an essential part of a physicist's development from graduate student to the laboratory workforce or an academic career: postdocs enhance their credentials as researchers while further developing an independent research identity and program. The data in Figure 8.7 emphasize the key role of postdoctoral training in forming and developing the future leaders of the nation's nuclear science enterprise. To prepare the trained senior workforce needed to enable the science of the future, these postdocs must continue in the field and build their skills in the coming decade.

Currently, a larger graduate student and postdoc workforce is needed to perform forefront experiments safely and effectively and to accomplish the necessary theoretical work that contextualizes these results and lays the foundations for nuclear physics discoveries. These early career scientists are on the front lines of efforts to analyze experimental data, develop nuclear models and tools necessary for the full exploitation of our experimental facilities, and synthesize the results. The nation will only fully benefit from the world-leading facilities and initiatives described in this document if a sufficient workforce of postdocs and students is available in the coming decade to produce substantial and timely insights from the data the facilities produce, take over as the next generation of scientific leaders, and continue the nation's record of nuclear science innovation, allowing the United States to maintain its world-leading position into the 2030s and beyond.

Figure 8.7. Over 1,000 students who were awarded a doctorate in nuclear science between 2012 and 2022 were tracked. *This plot shows the positions these students currently hold (% vs. year earned). Most students choose a postdoc as their first position (shown in years 2020–2022). Less than 40% stay in academia as permanent positions, instead using their talents in national laboratories and in the private sector (shown in 2012–2013). Unclassified industry jobs are not included and account for years with <100% [37].*

Barriers to recruiting and retaining graduate researchers and postdocs may have the unintended consequence of driving away talent. These barriers take many forms: financial, mental and physical health, and feelings of exclusion. In a climate survey of the nuclear physics graduate student community, the majority of respondents reported a struggle to meet daily needs, and many reported feeling financially precarious and unable to weather an unexpected cost. An analysis of the salaries of graduate researchers is presented in Sidebar 8.3. These concerns are expected to be amplified for first-generation students and those from traditionally underrepresented groups.

Therefore, as part of the first recommendation of this Long Range Plan, the nuclear science community recommends **raising the compensation of graduate researchers to levels commensurate with their cost of living—without contracting the workforce—lower-**

ing barriers and expanding opportunities in STEM for all, and so boosting national competitiveness.

Many of these students reported having been made uncomfortable in a research environment, especially women and those who identify as LGBTQ+. Moreover, graduate students are often considered both students and employees, which leads to an ambiguity in policies such as medical and family leave, adding an extra source of stress. These, and similar, barriers must be overcome in the coming years to grow and afford equal opportunity to all who participate in the nuclear physics workforce.

Ensuring a robust supply of well-trained nuclear scientists is essential not only for the government-funded workforce at national laboratories and universities but also for all the areas of the private sector where those trained as nuclear physicists are now driving the economy forward through hard work and innovation. Competition between these two paths for talent is healthy but has intensified in recent years, owing to the increasing emphasis on data skills in both theoretical and experimental nuclear science research and the need for those skills in the private sector.

8.7 CREATING INCLUSIVE AND WELCOMING ENVIRONMENTS

A nuclear physics–trained workforce is crucial to address the physical and technological challenges and opportunities espoused in this Long Range Plan as well as the many industries critical to US scientific and commercial leadership. The magnitude and complexity of those opportunities require strengthening and increasing the workforce engaged in nuclear science. Achieving this goal requires ensuring access to the entire available pool of talent by ensuring equal opportunity for all. It also requires ensuring that the scientists recruited are free to focus their energy on the challenging tasks at hand and are not lost from the community because of unexpected barriers. The highest priority of the nuclear science community in this Long Range Plan includes **expanding policy and resources to ensure a safe and respectful environment for everyone, thereby realizing the full potential of the US nuclear workforce**.

Failure to fulfill this recommendation jeopardizes the nation's international scientific and industrial leadership and squanders the significant investments made in nuclear physicists' early career training. Furthermore, a better environment is required to retain these recruits. It is important to examine the status of the community and its membership and seek to understand why, despite broad agreement that engagement in supporting equal opportunities, enhancing workforce participation, and fostering inclusion are necessary, our achievements lag our ambition.

8.7.1. New initiatives

Since the last Long Range Plan, the nuclear physics community has made decisive steps toward inclusion by implementing several new initiatives. The Division of Nuclear Physics (DNP) was the first American Physical Society division to instigate an Allies program, including active bystander training and session chair training before each DNP conference. DOE-NP has led the way in the development of the RENEW program, which addresses issues of retention and progression to graduate school by supporting research training of students from historically marginalized communities and first-generation undergraduates. The DNP will begin hosting research-based mentor training for early career faculty in 2023. The DNP CEU program has supported an increasingly diverse group of talented undergraduate students (i.e., first-generation, Pell grant eligible, veterans, disabled, underrepresented groups), and the CEU is collaborating with the DNP executive committee to provide a further enhanced CEU experience for all students by matching them with trained near-peer mentors. Ideally, mentor training workshops will be expanded to junior faculty and researchers during special conference sessions. The Center for the Improvement of Mentored Experiences in Research (CIMER) provides effective training to members of the community to facilitate mentoring workshops, enabling nuclear science members to work with other nuclear scientists for support and advice. The nuclear physics community and the federal agencies must work together and **continue to offer and expand these and other skills-development workshops at conferences and community events** to effectively cultivate an inclusive and equitable environment and ensure that all members of the community are fully included, supported, and retained.

In recent years, DOE has begun to require Promoting Inclusive and Equitable Research (PIER) plans and codes of conduct for conference proposals. NSF already requires a postdoctoral mentoring plan and broader impact statements in all grant proposals. Some NSF directorates are beginning to require evaluation of Safe and Inclusive work environment plans, although not yet in the Directorate for Mathematical and Physical Sciences. These important first steps will help build an inclusive community.

8.7.2. Addressing issues of belonging

Nuclear physics is inherently a collaborative endeavor, and those collaborations cross institutional and often international boundaries. In such a multi-insti-

Sidebar 8.2 The Benefit of Hands-On Nuclear Science Programs and Schools

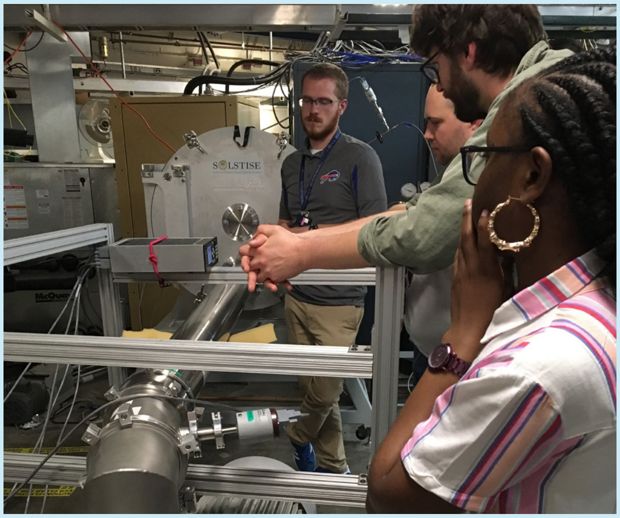
Programs in nuclear science that teach hands-on skills and provide opportunities for networking, such as the CEU program or various summer schools, can have a tremendous influence on the students who participate. Some choose to follow traditional career paths, whereas others continue to pursue completely different ventures—but many agree that their experiences helped them.

One such program is the Exotic Beam Summer School (EBSS); 2023 marks the 20th school. Unlike many other schools, the EBSS—which rotates among the five host institutions: ORNL, FRIB, Argonne, LBNL, and the different ARUNA facilities—features a daily hands-on component, allowing students to meaningfully interact with the state-of-the-art tools and techniques for radioactive ion beam measurements alongside experts in the field. Attendees gain experience with everything from machine learning algorithms to high-vacuum pumps.

In 2022, a Target Workshop, organized by ATLAS and the Center for Excellence in Nuclear Training And University-based Research (CENTAUR), hosted students for several days of training on how to fabricate a variety of target materials for accelerator-based measurements. Students brought these skills back to their home institutions and will carry these practical laboratory skills into their future careers.

Amber (right), a Louisiana State University student, watches target preparation with instructor Clay at Argonne's Center for Accelerator Target Science (CATS) [S60].

Air Force Institute of Technology student Connor (left) works with expert Claus (right) to learn the skills necessary to make target materials for nuclear physics measurements at Argonne National Laboratory [S61].



Students learn about different vacuum pump technologies at the 2019 Exotic Beam Summer School at Oak Ridge National Laboratory [S62].

Karla gets hands-on experience with a neutrino detector [S63].

tutional environment, with representation from many cultures, it is important to establish inclusive and equitable norms, especially when the power structures of early career training are considered. It is possible to meet the nation's economic and technological needs only in an inclusive environment where physicists can focus on the tasks at hand rather than fear aggression, harassment, or retaliation. Such situations can be exacerbated when multiple institutions are involved, and hence no clear path exists for preventing continued harm.

Codes of conduct or community agreements (CAs) are becoming more common, both for collaborations of all sizes and for conferences and workshops, where members of the community at all career stages and institutional backgrounds interface. Abiding by the CA of a given entity should be an explicit condition of membership in that entity. Violations of the CA should be taken at least as seriously as violations of other aspects of the entity's bylaws. CAs must permit the correction of behavior that, while not illegal, is detrimental to the group's health. The CA should be sufficiently nuanced to provide constructive and appropriate responses to varying levels of violation of the CA.

Finally, it is worth noting that the challenge of enforcing CAs includes determining appropriate reporting pathways and investigations, should a complaint be filed, and what forms of restorative justice or appropriate sanctions are available. These challenges can slow or prevent the adoption of CAs for many physics entities. **The funding agencies could supply significant help by providing guidance and trained individuals to assist physics entities in drafting CAs. In addition, user facilities should each have a clear, enforceable CA in place, applicable to all users and staff,** as is already the case for many laboratories in nuclear physics. This goal is particularly important because nuclear physics frequently involves 24 h shift cover, typically in pairs, in an otherwise isolated situation. This leadership by example would set a template for other organizations.

8.7.3. Strengthening the pipeline

As developing programs bring students from underrepresented groups into nuclear science, it is worth noting the differing barriers they may face. These students are often recruited from populations that are 2–3 times more likely to be economically disadvantaged. To ensure that these students—as well as others with challenging economic situations—are not excluded from the community by fiscal exigency, we must address the systemic and structural issues in the current nuclear physics infrastructure that leave many students struggling to remain in the field. Lack of financial stability can severely disrupt research progress, health and quality of life, and even the safety of the experimental facilities where nuclear research is performed. **Support must be sufficient to meet the daily needs of these early career nuclear scientists; otherwise they may be forced to seek an alternate career, and the newly recruited trainees may be lost from the community.**

In addition to addressing shortfalls in support of graduate researchers, support must also be provided to address these issues of financial precariousness in practical ways. Some examples include the following. Making some form of relocation support available to students moving from their undergraduate institutions to attend graduate school in a new location will facilitate retention and success. Access to some form of hardship funds to mitigate financial exigency related to unforeseen circumstances, such as unexpected medical emergencies and caregiver responsibilities, would enable students without external personal support to remain in the field. Such support would also help provide a sense of belonging because it shows real investment in their success.

Finally, challenging personal circumstances, exacerbated by uncertain support, may result in further losses, in particular of women, related to the need for family and medical leave. Given the ambiguous status of graduate students, institutional policies on family leave vary widely. **The funding agencies should provide and clearly communicate best practices and allowable procedures for graduate students and postdocs who find themselves in need of dependent care or medical leave.** The existing NSF Graduate Research Fellowships Program policy could provide a starting template for such policies.

8.7.4. Improving retention

Although many efforts have concentrated on increasing representation and reducing harassment in nuclear science, far less attention has been paid to ensuring long-term retention. The lack of work–life balance contributes to the choice by members of underrepresented groups to leave STEM; this problem compounds with other inequities faced by those minority groups, tipping the scale. According to a 2020 National Academies of Sciences, Engineering, and Medicine report, women drop out of academia more frequently than men. While there are many reasons someone chooses to leave the field, one reason is the difficulty in reconciling work and family life. Hence, despite recruitment efforts, the percentage of underrepresented groups occupying permanent positions in nuclear science has remained essentially constant since the last Long Range Plan.

Many aspects affect the ability to maintain a work–life balance, including the increase in administrative and service tasks and the effects of the COVID-19 pandemic.

Within the research community, increased pressures from administrative and service tasks can lead to work–life balance difficulties and ultimately issues with retention. Women and other underrepresented groups in nuclear physics, as in physics more broadly, often encounter the “service problem”: members of underrepresented groups are inherently tasked with more service work than their well-represented peers. This excess of service work, in addition to its contribution to work–life imbalance, can disrupt research output, which ultimately drives decisions such as tenure or promotion.

Scientists should be judged on the merit of their science, but the inherent biases in the current system used in hiring, promotion, and funding decisions must not be ignored. Data consistently show that those in STEM from underrepresented groups must have a higher scientific output to be judged as equal to their majority-group colleagues. This perception is particularly important if research budgets continue to shrink, because it will become even harder for scientists brought into the field from underrepresented groups to establish themselves. When combined with the additional service burdens described above, researchers from underrepresented groups can face an uphill battle to remain in the community and be successful.

Importantly, since the last Long Range Plan, a major worldwide pandemic significantly disrupted the research community, forcing the temporary closure of many laboratories and user facilities in nuclear science, and requiring the sudden rearrangement of personal and professional schedules to compensate for local and regional lockdowns. Within STEM broadly and nuclear science in particular, women shouldered a disproportionate fraction of the burden.

Many researchers worked from home, while skeleton staff continued keeping facilities running and ensured that previously existing safety requirements and new pandemic protocols were followed. The nuclear physics community was productive between 2020 and 2022: very little apparent decrease in publication activity occurred, many conferences shifted to a virtual format, and some laboratories offered the ability to participate in experiments remotely. These possibilities for remote participation improve access and benefit those whose travel funds are limited, but also further blur the lines between work life and home life. Moreover, evaluation of virtual/hybrid meetings indicates that participants find virtual conferences far less effective than in-person ones. This preference points to something fundamental about the face-to-face experience: it is very hard to replace the sustained attention and intense consideration of new ideas that make an in-person discussion productive and innovative. Furthermore, community formation is much harder in a virtual setting, so this type of workshop or conference runs the risk of providing only the facsimile of inclusion for those who are not already well connected in the nuclear science community.

Some of the damage caused by the pandemic to nuclear physics construction and instrumentation projects was redressed by the funding provided by the Inflation Reduction Act. As explained elsewhere in this document, this funding places the field in a strong position to move forward. However, we also emerged from the pandemic with many exhausted senior researchers, further eroded boundaries between work and home, and a graduate student body facing unprecedented mental health challenges. These broader repercussions on the community can only be addressed through sustained effort and attention. Federal funding agencies have been supportive, providing no-cost extensions and additional funding for graduate students whose time to degree was lengthened by the pandemic, but this support will remain necessary for at least the next few years.

8.8 SUMMARY AND PROPOSALS

The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments by the United States. To implement this recommendation, we propose a suite of actions, large and small, to create and sustain a healthy workforce that is central not only to the attainment of our scientific goals but also to the nation’s security, technological innovation, and prosperity.

Communication of the intrinsic value and societal benefit of nuclear science to a broad audience is necessary to attract students to the field. Coordination of educational and outreach efforts will enhance the return on investment. ***We propose a center where scientists, universities, and laboratories could share resources, pool best practices, and create a national footprint for the dissemination of nuclear science tools and resources for outreach and education.*** It will require a multiyear, significant, and sustained effort involving media professionals to produce a measurable increase in the pipeline for nuclear science.

Support for undergraduate research in the form of NSF REU and the recent RENEW traineeships form a crucial aspect of the nuclear science workforce development pipeline, with the CEU as a capstone experience fostering the retention of these undergraduates in the nuclear science community. **Continued investment in and refinement of these programs is essential.**

To genuinely afford equal opportunity to all in America and fully include those with lower socioeconomic status, support for graduate researchers must meet their individual economic needs without relying on supplemental family support. Thus, ***it is imperative to raise the compensation of graduate researchers to levels commensurate with their cost of living—without contracting the workforce—lowering barriers and expanding opportunities in STEM for all, thereby boosting national competitiveness***.

The community needs support from the agencies in the form of ***expanded policy and resources to ensure a safe and respectful environment for everyone, realizing the full potential of the US nuclear workforce***. This recommendation touches on many aspects of the workforce pipeline.

Graduate students are simultaneously employees and students, causing confusion around policies

Sidebar 8.3 Graduate Researcher Cost of Living

Graduate researchers are an integral part of the US nuclear workforce. This workforce advances fundamental science and uses their skills to support vital national interests, including those in medicine, security, and data science. These researchers spend 4–5 years honing their skills in universities and national laboratories across the country and the world as paid graduate researchers. Their research responsibilities could include overnight accelerator shifts, weeks away from home on experiments, and travel to present results.

Concern is growing that these researchers' wages have not kept up with the cost of living. This shortfall forces those from a variety of backgrounds out of the field, including students who are the first in their family to attend college, those from geographically diverse areas, and those who need to financially support their families.

Nuclear physics departments at universities across the country were asked for their researcher's 12-month salaries[1]. The 27 responses included both public and private institutions. All universities were grouped by population of their host city, and both public and private institutions were included in each category as shown in the table below.

Identification	Population	Number of private institutions	Total number of institutions
Major metro	>1.5 million	3	5
Large city	450,000–900,000	2	5
City	100,000–400,000	2	11
College town	<80,000	2	6

The institutions and the amounts below the cost of living are graphed in Figure 1. The cost of living was calculated for each location[2] assuming a single-income adult with no dependents. The results are unacceptable. Only two institutions pay their researchers within $500 of the recommended amount needed to live in their respective areas, and seven institutions pay $8,500 less than necessary to meet their basic needs. This shortfall amounts to an average of more than $450 per month, which limits an individual's ability to pay for food, prescription medicine, and rent.

This sentiment was echoed in the survey of graduate researchers: 65% of the 243 respondents struggle to meet basic costs such as food, housing, and transportation. Many expressed deep concern about their ability to pay and procedures that would support these students. ***Funding agency policies on areas such as medical and family leave should be formalized and clearly communicated*** to enable principal investigators to effectively and inclusively support their research teams to success. At a minimum, we recommend that the NSF Graduate Research Fellowships Program policy serve as a template for broader DOE and NSF statements.

To facilitate the growth of a safe, welcoming, and inclusive community, all members of each physics entity should receive practical information and effective training, and they should be governed by appropriate CAs. ***Therefore, we recommend supporting appropriate skills development in workshops and targeted sessions at conferences to effectively cultivate an inclusive and equitable environment for all.*** This recommendation includes mentoring workshops for young faculty and staff at divisional meetings, using available funds to help defray the costs of additional travel expenses. To ensure this environment is communicated clearly, ***all national laboratories should have a CA in place that applies equally to laboratory staff and laboratory users, and the agencies should provide resources to support nuclear physics collaborations, communities, and networks to establish and maintain enforceable community agreements.***

We request that the federal agencies set a strong example by considering work–life balance when

for basic needs or meet an unexpected expense without outside help (e.g., family members). This number has increased from the 2004 Education in Nuclear Science Report, which stated that 20% of graduate students did not think they were paid enough to ensure an adequate standard of living. To capitalize on the talents of those across all circumstances, we must invest in the future workforce.

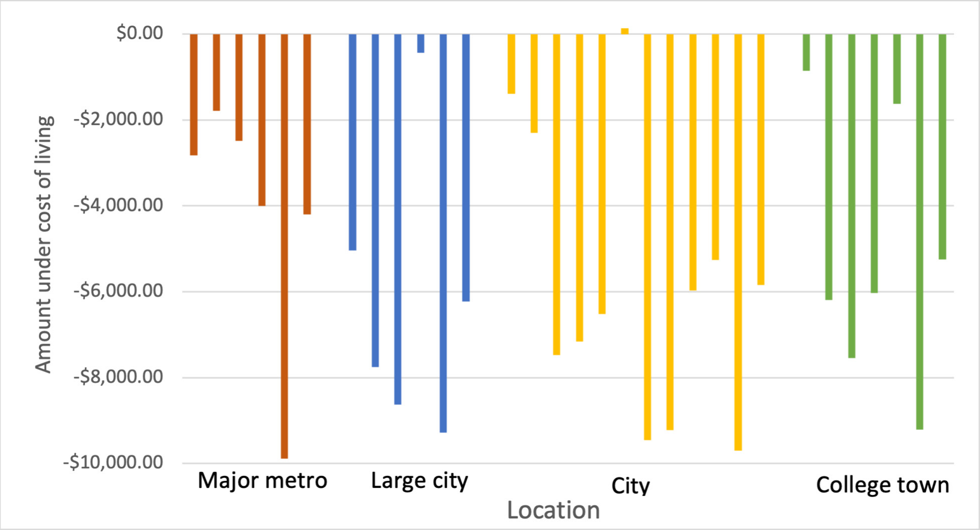


Figure 1. Graduate researchers are paid an average of $5,460 per year less than the cost of living for their location. The institutions are grouped by population of the host city or town [S64].

Although the ability to raise graduate researcher salaries is contingent upon local institutional policy and practices, institutions and government agencies are starting to collaborate to offer relief. This issue must be addressed to reduce barriers to participation in nuclear science for all members of the US population.

[1] If a nine-month salary was reported, it was adjusted to 12-months for equal comparison.

[2] The https://livingwage.mit.edu/ calculator was used, taking into account the location of each institution.

they structure remote review panels to account for the additional family responsibilities panelists may face when not on travel. They should also provide advance notice and sufficient review time for peer reviewing in general. ***Proposal review and panel training and criteria should account for the differing service and teaching burdens*** faced by women, underrepresented principal investigators, and those at non-R1, minority-serving institutions, and historically Black colleges and universities. Furthermore, these criteria should place explicit value on community service and equity and inclusion-fostering structures and activities that benefit the whole nuclear physics community. To alleviate some of this burden, ***administrative support funds should be allocated to reduce the service load incurred by researchers who are awarded RENEW and other grants that focus on research and retention activities***. The talents of all in the nation must be drawn upon to make this new era of discovery for nuclear science a reality.

9 FACILITIES

9.1 OVERVIEW

Nuclear physicists conduct cutting-edge research by developing and employing a diverse set of facilities and tools. These facilities and tools enable not only discovery science but also applications of broad societal impact and the development of a diverse and talented STEM workforce for the nation (Sidebars 9.1, 9.2). Just as the physics spans multiple scales—energy, distance, mass—so are the facilities and instrumentation used to probe that physics. Since the 2015 NSAC Long Range Plan, several major new user facility/upgrades were completed, including FRIB, the 12 GeV upgrade of CEBAF, and the sPHENIX collider detector at RHIC. During this time, the future EIC became an official DOE project, and the existing RHIC site at BNL was chosen as the location for the EIC.

Hosting what will soon be the heavy-ion accelerator with the highest beam power, FRIB enables scientists to make discoveries about the properties of rare isotopes, nuclear astrophysics, fundamental interactions, and applications for society. The DOE Office of Science's newest scientific user facility—completed in 2022 ahead of schedule and on budget and with first science results already published—uniquely affords access to about 80% of all isotopes predicted to exist up to uranium.

The ATLAS facility provides heavy-ion beams with precision energies, near the Coulomb barrier, to study emergent behavior of collections of protons and neutrons. Upgrades continue to keep the facility at the forefront of accelerator technology while increasing its scientific reach in the field of nuclear structure and nuclear astrophysics research, with beam energies and intensities not available elsewhere in the United States. CEBAF at Jefferson Lab is a unique and world-leading facility for precision electron scattering measurements at the luminosity frontier. The CEBAF accelerator program, now providing electrons of up to 12 GeV and utilizing and planning for a suite of dedicated instruments, is producing powerful scientific results. A CEBAF upgrade plan, including positron beams and a novel energy upgrade, is being pursued. RHIC at BNL is the only collider in the world capable of colliding heavy ions and polarized protons to study the structure of the nucleon and matter that existed in the early universe. At RHIC, technological breakthroughs led to the successful completion of the Solenoidal Tracker at RHIC (STAR) Beam Energy Scan program. A completely new collider detector, sPHENIX has been installed at RHIC in spring 2023 and is currently being commissioned. The 40-fold improvement over the design average luminosity of the gold–gold collisions allows full scientific exploitation of RHIC by sPHENIX and the upgraded STAR detector before RHIC operation ends and the EIC construction starts.

The EIC will be a new, large-scale particle accelerator facility that will provide precision 3D pictures of the quarks and gluons inside nuclear matter. The EIC will be the first accelerator in the world capable of colliding high-energy beams of polarized electrons with heavy ions, polarized protons, and polarized light ions. The Electron–Proton/Ion Collider (ePIC) detector, a multipurpose, large-acceptance detector designed to reconstruct all the particles created in the intense collisions, will be located at one of two possible interaction regions. The scientific promise and cutting-edge technologies in building the EIC have sparked interest from the international nuclear and particle physics communities and continue to draw on the expertise of the top accelerator, detector, and computing scientists in the world.

Dedicated facilities, such as the ARUNA laboratories and the LBNL 88-Inch Cyclotron Facility, make unique searches into a variety of topics—such as low-energy reactions or superheavy elements—accessible, while providing vigorous training to the next generation of STEM leaders. Nuclear physics research is vibrant at many university laboratories and dedicated facilities around the country, providing excellent training grounds for undergraduate and graduate students and postdocs in frontier nuclear physics research with hands-on experiences that are widely applicable to many sectors of society in STEM and related fields. Underground laboratories and neutron facilities are important tools for the study of fundamental symmetries and neutrinos. These studies address some of the most fundamental questions in nature. Although these studies are synergistic with particle physics and cosmology, unique nuclear physics tools and techniques can enable discovery science at the low-energy precision frontier. Underground laboratory space is limited, necessitating international coordination to site these experiments.

Particle detectors, accelerators, and computing play important roles in experimental nuclear physics research. Nuclear physicists have made significant contributions to the development of new particle detectors and their applications to areas such as medical diagnostics and treatments and national security, including radiation effects on electronics. Computing and data science, including artificial intelligence and machine learning, are becoming increasingly important in nuclear physics research, and contributions from nuclear physics to areas such as algorithms, data storage, high-performance and high-throughput computing, and quantum computing are well recognized. Accelerator science and technology and their applications are critical components of nuclear physics capabilities, enabling the nuclear physics community to deliver world-leading research and applications with broad societal benefits (Chapter 11).

Nuclear physics is inherently international, and US nuclear scientists are actively collaborating with researchers around the globe, and they are leading and participating in experiments and collaborations at facilities outside the United States. This chapter presents these world-leading facilities, tools, and unique capabilities in the United States in the international context.

9.2 NATIONAL ACCELERATOR FACILITIES

9.2.1. Facility for Rare Isotope Beams

FRIB, located on the campus of Michigan State University, is the newest scientific user facility for the DOE SC Nuclear Physics (NP) program, with more than 1,800 registered users. FRIB enables scientists to make discoveries regarding the properties of atomic nuclei, their role in the cosmos, and the fundamental symmetries of nature, using previously unavailable beams of rare isotopes. The wide range of isotopes also enables development of new applications for society and the nation. The discoveries at FRIB will illuminate answers to grand-challenge questions such as the ultimate limits of nuclear existence on the chart of nuclides, the astrophysical sites and isotopic pathways to heavy-element production in the Cosmos, and the origin of the matter-antimatter asymmetry in the Universe. As the only DOE SC user facility located on the campus of a research-intensive university, FRIB has been a magnet for students studying not only nuclear science but also accelerator physics, cryogenic engineering, and radiochemistry—all areas identified as in short supply for the nation and critical to US economic competitiveness, nuclear security, and nonproliferation efforts.

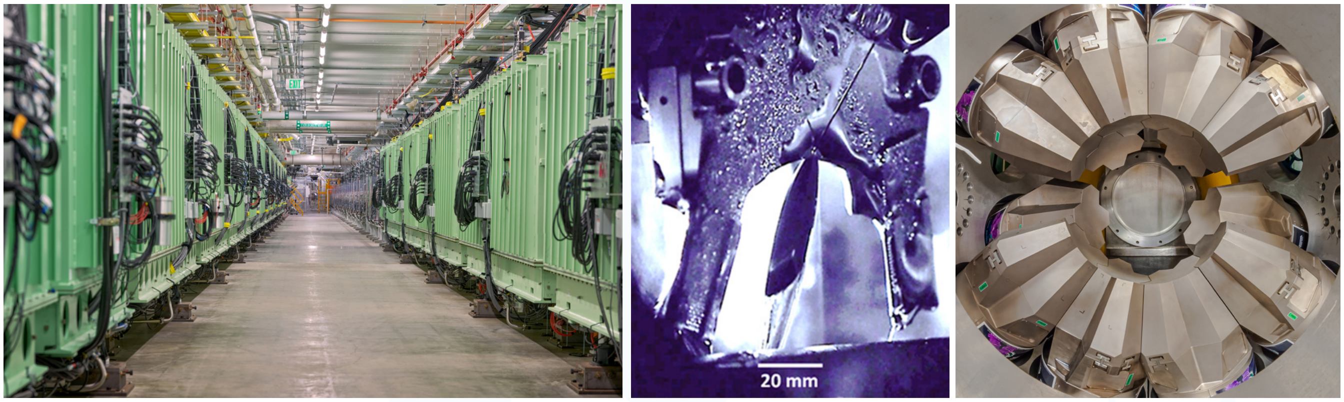


Figure 9.1. The Facility for Rare Isotope Beams. *(left) At the heart of FRIB is its 400 kW SRF linear accelerator using 46 acceleration modules (green). (middle) Photograph of the liquid lithium film formed in the charge stripper. (right) LBNL-built Gamma-Ray Energy Tracking In-Beam Nuclear Array (GRETINA) mounted at FRIB [38].*

FRIB, the world's premier rare-isotope facility, is ramping up to 400 kW of beam power (Figure 9.1). The rare isotopes are produced by fragmentation or fission of stable primary beams at 50% of the speed of light. Ions of any stable element can be accelerated in FRIB's 400 kW superconducting radio frequency (SRF) linear accelerator to at least 200 MeV/nucleon, providing the highest-intensity beams at half the speed of light. Following the collision of the primary beam with a target, the produced rare isotopes of interest are selected using FRIB's fragment separator and then guided to experimental areas where the short-lived nuclei can be used directly as fast beams for reactions, they can be stopped in a detection system that measures their decays, or they can be slowed in a gas cell and used in precision experiments after extraction or made into reaccelerated beams of pristine quality and energies ranging from hundreds of kiloelectronvolts to well above the Coulomb barrier. FRIB is the only facility in the world that offers isotopes of any element lighter than uranium for studies as fast, stopped, and reaccelerated beams, including over 1,000 isotopes never produced on Earth before. Soon, the unused rare isotopes that are produced alongside the nuclei of interest will be harvested in research quantities and, after chemical separation in hot cells, will be used to develop broader applications of FRIB-unique rare isotopes. FRIB is also outfitted with a single-event effects test beamline that is used by scientists from the commercial sector or government agencies to probe the response of electronic components and materials to heavy-ion beam irradiation.

The first recommendation of the 2015 Long Range Plan called for the expeditious completion of FRIB, and this goal was accomplished in January 2022, ahead of schedule and on budget. The first scientific user experiment was conducted in May 2022, and the first results were published later that year. Remarkable technical accomplishments were made along the way, such as the development and use of a liquid lithium stripper to change the charge state of the primary beam ions (in collaboration with Argonne) and the acceleration of multiple charge states of the primary ion beam.

FRIB's science program requires state-of-the-art scientific instrumentation aligned with the identified science drivers and increasing facility capabilities. Since the first day of facility operations, the FRIB users have had access to the existing state-of-the-art instrumentation at the laboratory. In parallel, new scientific instrumentation is being developed and constructed to harness the full discovery potential of the new facility. For example, the HRS, which extends the scientific reach to neutron-rich isotopes by a combined production-rate and luminosity increase of up to a factor of 100 for nuclear reactions, has CD-1 approval. An upgrade from the FRIB Decay Station Initiator (FDSi) to the FDS is presently in early stages, aiming to revolutionize decay spectroscopy. For use with FRIB's world-unique reaccelerated beams, a device such as ISLA, in the conceptual design phase, will be needed to provide the necessary channel selection for a broad range of nuclear reactions.

The community has endorsed the science case for doubling FRIB's energy to 400 MeV/nucleon for uranium and to higher energies for lighter ions (FRIB400). FRIB400 doubles FRIB's reach along the neutron dripline from zinc to neodymium; increases luminosity for spectroscopy in key regions of the nuclear chart by up to two orders of magnitude; brings more nuclei into reach, which is important for the r-process during neutron-star mergers and for neutron star crust processes; compresses asymmetric nuclear matter to densities required for experiments relevant to multi-messenger astronomy; enables fast-beam reactions to be done in the optimal energy regime for their interpretation; and increases the yield of many harvested isotopes by a factor of 10. In anticipation of this science potential, space was provided in the FRIB tunnel to upgrade the accelerator energy. The state-of-the-art accelerator technology has been proven by prototyping. The upgrade can be implemented in a staged approach during regular shutdowns with no major interruption of the FRIB science program. At each stage, the gain in primary beam energy would translate into increased science potential. The FRIB fragment separator and the beam distribution to key detector systems are well matched to the upgrade.

9.2.2. Argonne Tandem Linac Accelerator System

The ATLAS national user facility at Argonne is the premier DOE-funded stable-beam facility for nuclear physics. The ATLAS research programs focus on key questions that are central to our understanding of matter and of the astrophysical processes that generate energy and produce elements in the stars. They also focus on important societal applications such as next-generation nuclear reactors and nuclear forensics. The precision beam energies provided by ATLAS (i.e., in the vicinity of the Coulomb barrier) cover the energy domain where nuclear reactions occur in the cosmos and the optimum energy to probe the single-particle structure of the nucleus. The full range of stable ions from protons to uranium can be produced and accelerated in the world's first superconducting linear accelerator for heavy ions to energies up to 20 MeV/A. These ions can be delivered to one of several unique, world-class, state-of-the-art instruments. The facility was enhanced a decade ago with the addition of the Californium Rare Isotope Breeder Upgrade (CARIBU), which allows harvesting of world-unique beams of neutron-rich rare isotopes related to nuclear structure, astrophysics and applications to nuclear security, nuclear energy and nuclear medicine.

Upgrades since the last Long Range Plan focused on increasing the intensity and purity of radioactive beams, increasing the beam time on target, and adding experimental capabilities to take advantage of these more intense beams (Figure 9.2). The purity of the reaccelerated neutron-rich beams from CARIBU has been improved by the addition of an electron beam ion source (EBIS), which minimizes stable beam contamination. The Argonne In-Flight Radioactive Ion Separator (RAISOR) was developed and installed to improve the intensity and purity of light radioactive beams produced by the in-flight technique. The last eight accelerating structures of ATLAS have been replaced by high-performance quarter-wave resonators. As a result, the maximum energy of the facility was increased by 4 MeV/u for mid-mass nuclei. Modern accelerating structures at ATLAS assembled in ultraclean environments also drive the need to maintain these clean systems and to develop and improve upon techniques to mitigate performance degradation and to support reliable operation at ATLAS and all other current and future nuclear physics accelerator facilities. The addition of a novel, highly redundant, solid-state amplifier driving the radio frequency quadrupole section of the linac along with a new radiation interlock system further improve the facility's reliability and safety. Experimental equipment has also been significantly improved, with new devices added alongside existing unique instrumentation such as the Canadian Penning Trap, the solenoidal HELIOS, the Beta Paul Trap, and the Fragment Mass Analyzer. For example, the addition of a digital data acquisition system for the Gammasphere spectrometer has improved event throughput by roughly an order of magnitude in many cases. This upgrade, coupled to the new Argonne Gas-Filled Analyzer, yields the most powerful setup to study the structure of the heaviest nuclei by identifying excited states in the measured isotopes. A new low-background experimental area was also added to improve the sensitivity of decay spectroscopy experiments with unaccelerated CARIBU beams.

Sidebar 9.1 Workforce Development at DOE Accelerator Facilities

The DOE Nuclear Physics Accelerator User Facilities not only enable discovery science, but also harbor technologies and innovations that attract and enable diverse and talented workforce development that fills unique national needs.

Left: Students, postdoc and visiting scientist working on the Backward Angle Neutron Detector (BAND) in Hall B at JLab [S64]. Right: Graduate students from Howard University and Florida A&M University working on the sPHENIX detector at RHIC at the Brookhaven National Laboratory. Workforce with such skills is in high demand not just in science and at national laboratories but also in the high-tech industry [S65].

A collaboration between FRIB and the MSU College of Engineering, the MSU Cryogenic Initiative combines classroom education with training in cutting-edge cryogenics, accelerator, and superconducting radio frequency sciences and technology at FRIB. The demand for cryogenic engineering support has increased continuously during the last decade, so this initiative fulfills a national need [S66].

Early career staff of the operations crew preparing for an upgrade at the ATLAS Facility at Argonne National Laboratory. This upgrade has allowed for the facility to supply beams of mid-mass nuclei at over 20 MeV/A, paving the way for critical measurements with neutron-rich beams from nuCARIBU [S67-68] .

The ATLAS facility delivers about 6,000 h of beam time per year to its users with high reliability, and an additional 2,000 h or more per year of unaccelerated neutron-rich beams harvested from CARIBU. Even with 8,000 h of beam time delivered per year, the facility is highly oversubscribed and can only accept about one-third of the proposals submitted to the Program Advisory Committee. The ATLAS Multi-User Upgrade, which is currently underway, will enable the delivery of ATLAS beams to more than one experiment at a time, significantly increasing the effective hours of beam time delivered. The intensity of the CARIBU beams will also be increased by the nuCARIBU upgrade, which will produce neutron-rich isotopes via neutron-induced fission on actinide targets. The nuCARIBU driver will replace the californium-252 spontaneous fission sources in use at CARIBU and increase the fission product intensity exiting the gas cell by roughly one order of magnitude.

New capabilities are being added to access new regions of neutron-rich rare isotopes of heavier elements critical to understanding the formation of the heaviest elements in the cosmos. Using a different reaction mechanism to produce these isotopes than those employed at existing facilities such as FRIB will enhance the field by generating more of these heavier, neutron-rich elements than is available elsewhere. Combining this reaction mechanism with the techniques developed at ATLAS for the CARIBU facility will allow these new isotopes to be produced and separated with sufficient intensity to enable first studies of their properties. This world-unique upgrade, called the *N* = 126 factory after the neutron number of the isotopes of interest, will provide access to this unexplored region starting in FY 2023 (Sidebar 5.3). It is also envisioned that capabilities will be added to reaccelerate these neutron-rich isotopes in the next 5–10 years.

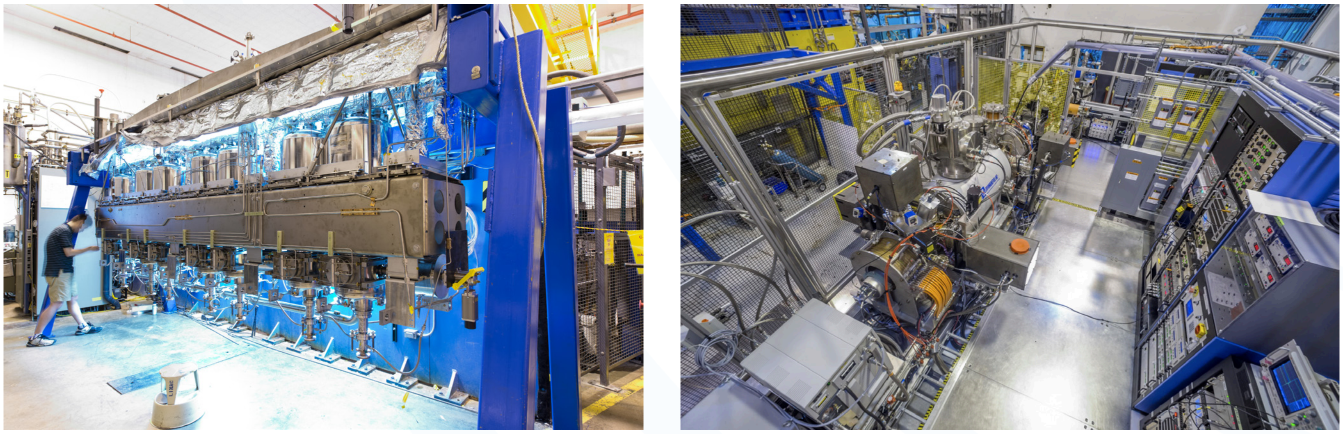


Figure 9.2. ATLAS upgrades. *(left): A string of superconducting cavities and focusing solenoids developed for the recent intensity and energy upgrade at ATLAS. (right): The EBIS developed to increase the purity of neutron-rich ion-beams extracted from CARIBU for reacceleration in ATLAS [39].*

The availability of target fabrication capabilities and associated trained workforce is critical to successful experiments at ATLAS, FRIB, and other accelerator facilities. The Physics Division at Argonne maintains a target development laboratory, the national Center for Accelerator Target Science (CATS), which directly supports ongoing low-energy nuclear physics research undertaken at the ATLAS facility and elsewhere. Multiple facilities within Argonne are maintained as part of this effort. CATS can produce stable or radioactive targets from natural or isotopically enriched material for a wide range of elements. In any given year, CATS delivers hundreds of targets to various stakeholders, including dozens to laboratories other than ATLAS in the United States and abroad.

9.2.3. 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory

LBNL is home to the 88-Inch Cyclotron Facility, a sector-focused 300 ton machine with both light- and heavy-ion acceleration capabilities. Most heavy ions through uranium can be accelerated to energies that vary with the mass and charge state. The 88-Inch Cyclotron supports ongoing research programs in nuclear structure and astrophysics, heavy-element studies, and technology R&D. It also hosts the Berkeley Accelerator Space Effects (BASE) Facility, which provides well-characterized particle beams that mimic the harsh environment found in space. Major instrumentation at the 88-Inch Cyclotron includes the Berkeley Gas-Filled Separator and the novel For the Identification of Nuclide A (FIONA) apparatus, both for the study of superheavy elements, and the superconducting Versatile Electron Cyclotron Resonance (ECR) Ion Source for Nuclear Science (VENUS), one of the most powerful ECR ion sources in the world. FIONA, just recently commissioned, can determine the masses of superheavy isotopes to within one mass unit. The United States—and LBNL in particular—have a storied history of discovering new superheavy elements and exploring their unique nuclear physics and chemistry. The US heavy element community has laid out an ambitious plan to maintain US leadership in this important field and mount a search for superheavy elements beyond oganesson (Z = 118). LBNL's 88-Inch Cyclotron facility plays a vital role within this effort because it is the US accelerator laboratory devoted to heavy-element research, an endeavor that requires long, dedicated beam times with very high-intensity stable beams and specialized instrumentation for the efficient identification and characterization of the handful of new atoms produced.

9.2.4. Continuous Electron Beam Accelerator Facility at Jefferson Lab

CEBAF has been delivering the world's highest intensity and highest precision multi-GeV electron beams for more than 25 years, probing the partonic structure of nucleon and nuclei and studying hadron spectroscopy. While advancing nuclear science, the laboratory provides critical training in areas of national need and spurs technological innovation, as evidenced by the recent creation of the Biomedical Research and Innovation Center at Jefferson Lab. The CEBAF 12 GeV energy upgrade project was completed in fall 2017, beginning a new era at the laboratory. The kinematic landscape for worldwide deep inelastic scattering facilities, including CEBAF at 12 GeV, is shown schematically in Figure 9.3. Because of the small cross sections and the need for multiple kinematic variables to be studied precisely, measurements in the valence quark region require high luminosity. The valence region plays an important role in the charge, spin, and other fundamental aspects of the nucleon. Even looking simplistically at only the Bjorken x-variable shown in Figure 9.3, this valence regime is the purview of CEBAF at Jefferson Lab. A potential staged upgrade of the CEBAF accelerator has been under investigation for some time (Section 9.7) that would initially provide a 12 GeV polarized positron beam, and then a 22 GeV electron beam, while maintaining the world-leading luminosity. This capability would uniquely provide precise information on the role of two-photon exchange in lepton–hadron scattering, allow access to a new sector of hadron spectroscopy, and offer an unprecedented view of the complex nucleon structure in the valence region, one not accessible at other machines.

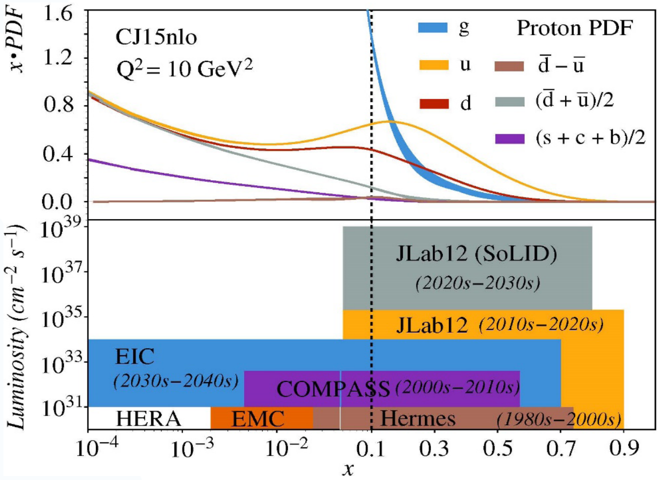


Figure 9.3. Landscape of the QCD program at the current and approved deep inelastic scattering facilities. *The Solenoidal Large Intensity Device (SoLID) expands the luminosity frontier in the large x region, whereas the EIC does the same for low x. The glue distribution is off scale below x=0.1. Together, SoLID at Jefferson Lab and the EIC at BNL will, throughout the next several decades, cover a broad and largely complementary kinematic range, with Jefferson Lab probing key physics and providing precision data in the high-x region [40].*

The 12 GeV era at Jefferson Lab has included a suite of new experimental equipment. Hall A has transitioned into a multiple experiment installation hall, most notably facilitating the SBS experiments, MOLLER, and SoLID equipment and programs. The SBS program involves two open, single-bend, resistive spectrometers and two large standalone calorimeters for electromagnetic and hadron calorimetry. This apparatus will enable studies of the electromagnetic structure of the nucleon to an unprecedentedly small length scale. MOLLER will measure parity-violating asymmetries in electron scattering off atomic electrons in a high-power liquid hydrogen target by rapidly flipping the longitudinal polarization of the 11 GeV electron beam. This asymmetry is proportional to the weak charge of the electron, which in turn is a function of the electroweak mixing angle, a fundamental parameter of electroweak theory.

With the study of nucleon structure evolving from single- to multidimensional measurements that employ exclusive processes and the quest for understanding the origin of the proton mass based on studies of near-threshold meson production, frontier QCD research requires, first and foremost, higher statistics. Similarly, parity-violating electron scattering requires increasing statistical precision to test the Standard Model at low to medium energies. Such emerging needs from both QCD and fundamental symmetries call for a truly large-acceptance, high-intensity device to fully capitalize on CEBAF's high-luminosity beam. SoLID, planned for Jefferson Lab as an integral part of the CEBAF 12 GeV program, was designed to meet such needs. SoLID will use the CLEO II 1.4 T solenoid magnet and a large-acceptance detector system to operate at luminosities among the highest at Jefferson Lab. The realization of SoLID in Jefferson Lab Hall A is shown in Figure 9.4.

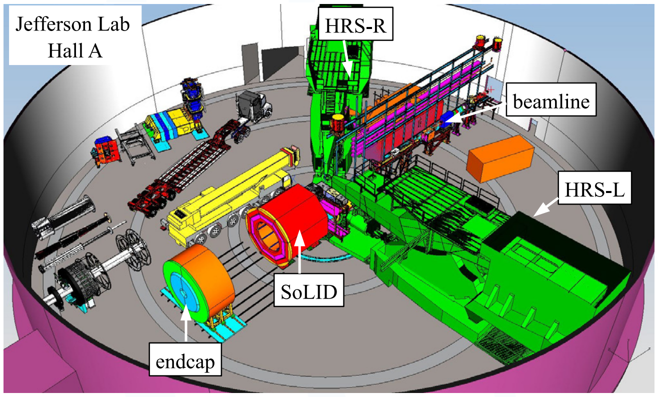


Figure 9.4. Schematic layout of SoLID in Hall A of Jefferson Lab.*The endcap is pulled downstream to allow detector installation and reconfiguration. The two high-resolution spectrometers (HRS-L and HRS-R, not in use) are parked at backward angles [41].*

Hall B is equipped with a permanent 4π CLAS12 spectrometer for operations at 12 GeV beam energy but can accommodate different experimental setups for dedicated measurements such as the Proton Radius (PRad) and the heavy-photon search experiments. This spectrometer efficiently detects charged and neutral particles over a large fraction of the full solid angle. CLAS12 is based on a dual-magnet system with a superconducting torus magnet that provides a largely azimuthal field distribution that covers the forward polar angle range up to 35°, and a solenoid magnet and detector covering the polar angles from 35° to 125° with full azimuthal coverage. CLAS12 can operate at a luminosity that is one order of magnitude higher than the previous CLAS6 in the 6 GeV era. CLAS12's capabilities are being used in a broad program to study the structure and interactions of nucleons, nuclei, and mesons, using polarized and unpolarized electron beams and targets for beam energies up to 11 GeV.

In Hall C, the base apparatuses are the High-Momentum Spectrometer (HMS) and Super High Momentum Spectrometer (SHMS). These several-millisteradian acceptance devices can reach momenta of more than 6 GeV and 11 GeV, respectively, with momentum acceptance exceeding 10%. Momentum reconstruction resolution and accuracy at the 0.1% level are routinely achieved. These spectrometers can be placed at scattering angles as small as 5.5° and 10.5° with sub-milliradian pointing accuracy. They may be used individually or together or with other detectors, and they have well-shielded detector stacks. This configuration provides a unique ability to measure small cross sections, which demand high luminosity and facilitate careful studies of systematic uncertainties. The HMS and SHMS have well-shielded detector huts, high-power cryotargets, and a 1 MW beam dump, allowing for routine operation at high luminosities. When SHMS and HMS are rotated to large angles, the hall, with its large beam height, provides the flexibility to install a wide variety of additional detectors and targets, such as the Neutral Particle Spectrometer, Compact Photon Source, or tensor-polarized deuterium target.

Hall D uses a beam of polarized real photons and a nearly hermetic magnetic spectrometer, optimized for the GlueX experiment for meson spectroscopy studies. The trajectories of charged tracks are detected with the help of the central and forward drift chambers, while photons are measured in the barrel and forward calorimeters (BCAL and FCAL). The start counter, the TOF counter, and BCAL provide the timing measurements for event selection and particle identification. For the GlueX-II experiment, the spectrometer was augmented with a detector of internally reflected Cherenkov light. Whereas the GlueX experiment uses a relatively open trigger based on the calorimeter signals, providing high efficiency for most photoproduction processes, GlueX-II runs at a post-collimator photon flux in the coherent peak of about 50 MHz and a data acquisition event rate of 80 kHz. Other experiments in Hall D include measurements of neutral η meson lifetime. Plans for Hall D include the approved eta factory experiment and the proposed intense K–long K_L beamline that would serve new experiments in the GlueX spectrometer.

9.2.5. Relativistic Heavy Ion Collider at Brookhaven National Laboratory

The primary scientific mission of RHIC is to explore the unique quantum many-body phenomena exhibited by matter governed by QCD under extreme conditions analogous to those attained in the first microseconds of the universe following the Big Bang. A secondary mission is to quantify the contributions of gluons, sea quarks, and antiquarks to the overall spin of the proton. RHIC's versatility enables it to collide ions ranging from protons to uranium, including any combination of different ion species. Gold beams in RHIC reach energies up to 100 GeV per nucleon, and polarized protons reach energies up to 255 GeV. RHIC is the only polarized proton collider in the world. Major discoveries made at RHIC include the transition at very high temperatures from ordinary nuclear matter to a quark–gluon plasma (QGP) that behaves as a nearly viscosity-free liquid and the observation that gluon spin contributes significantly to the proton spin. In addition to enabling discovery science and technological innovations, RHIC attracts researchers and technical staff from around the world, contributing to the local economy through jobs and purchases of goods and services while inspiring and training the nation's STEM workforce. Running RHIC also enables the production of critical isotopes used in medicine, industry, and national security as well as studies of space radiation to protect astronauts and test electronics.

After more than a decade of discovery science, the 2015 NSAC Long Range Plan identified two important goals for the RHIC science mission: "There are two central goals: (1) Probe the inner workings of the QGP by resolving its properties at shorter and shorter length scales…as is a state-of-the-art jet detector at RHIC, called sPHENIX; (2) Map the phase diagram of QCD with experiments planned at RHIC."

The STAR experiment has taken data each year since RHIC began operations in 2000. STAR physics continues to evolve as a highly versatile and diverse program with several major detector upgrades throughout the years. These major upgrades focused on improving particle identification and vertex reconstruction, and the most recent upgrade extended the forward rapidity coverage with contributions from US and international funding agencies. The STAR collaboration is a pioneer or early adopter of the use of several new detector technologies, including multigap resistive plate chambers, monolithic active pixel sensors, gas electron multipliers, and silicon photomultipliers (SiPMs). Following the 2015 NSAC Long Range Plan, the STAR collaboration completed a 3 year beam energy scan campaign in the summer of 2021. This program covered 13 energies, including 7 new fixed-target energies, the lowest of which was 3 GeV per nucleon pair for gold–gold collisions. Such low energies at RHIC were possible because of the great success of a low-energy RHIC electron cooling technique developed at BNL, the first-ever successful demonstration of electron cooling with bunched beams. Another major RHIC achievement since the 2015 Long Range Plan was Run 2018 with ruthenium–ruthenium and zirconium–zirconium isobar collisions in which species changed every store with the same leveled luminosity. It required stochastic cooling, enriched species, and two independent ion sources with enriched ruthenium-96 from ORNL's isotope program. It is part of DOE IP, which grew significantly under the auspices of DOE NP before becoming a separate office in the DOE in FY 2022. The STAR collaboration conducted blind analyses of the data from ruthenium–ruthenium and zirconium–zirconium collisions and achieved unprecedented precision (0.4%) in experiments from heavy-ion collisions in their search for the chiral magnetic effect.

As seen in Figure 9.5, sPHENIX is a new collider detector at RHIC designed to use energetic probes (e.g., jets, heavy quarks) to study the QGP with unprecedented precision and to address the following question: How does the structureless "perfect" fluid emerge from the underlying interactions of quarks and gluons at high temperature? The sPHENIX detector is the first RHIC detector that employs a superconducting magnet—the repurposed BaBar magnet from the SLAC National Accelerator Laboratory (SLAC), which has a central field of 1.4 T. The sPHENIX detector package consists of an outer hadronic calorimeter, inner hadronic calorimeter, electromagnetic calorimeter, TPC, monolithic active pixel sensor–based vertex detector (MVTX), intermediate silicon strip tracker (INTT), minimum bias detector, and sPHENIX event plane detector. The combination of TPC, MVTX, and INTT will provide excellent position measurement of charged particles from RHIC collisions to determine their momenta. Additionally, a TPC outer tracker outside the TPC provides fixed spatial points and uses tracks to reconstruct beam-induced space–charge distortions to achieve optimal TPC performance. The sPHENIX upgrade includes major contributions from DOE, as well as contributions from NSF and international contributions from China, France, and Japan. The sPHENIX detector was designed and built as a powerful "microscope" to take advantage of the large luminosity increase, compared with its originally designed value, of the RHIC gold–gold luminosity that was achieved in 2016 to probe the inner workings of the QGP. It will close the gap in kinematic reach from RHIC to the Large Hadron Collider (LHC), providing complementary studies of hard probes in different QGP conditions with variable momentum and angular scales by using reconstructed jets, charged particles, and direct photons. An important pillar of the sPHENIX science program is quarkonium spectroscopy to characterize the QGP on different length scales—specifically by simultaneously studying three length scales involving $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. The sPHENIX experiment will also offer a vast increase in open heavy-flavor precision to study parton energy loss in QGP by varying the mass and momentum of the probe. It will also open a new channel at RHIC by studying and tracking jets with rare quarks. The sPHENIX detector and forward-upgraded STAR will collect data in FY 2024 and FY 2025. After RHIC operations conclude in 2025, EIC construction will start.

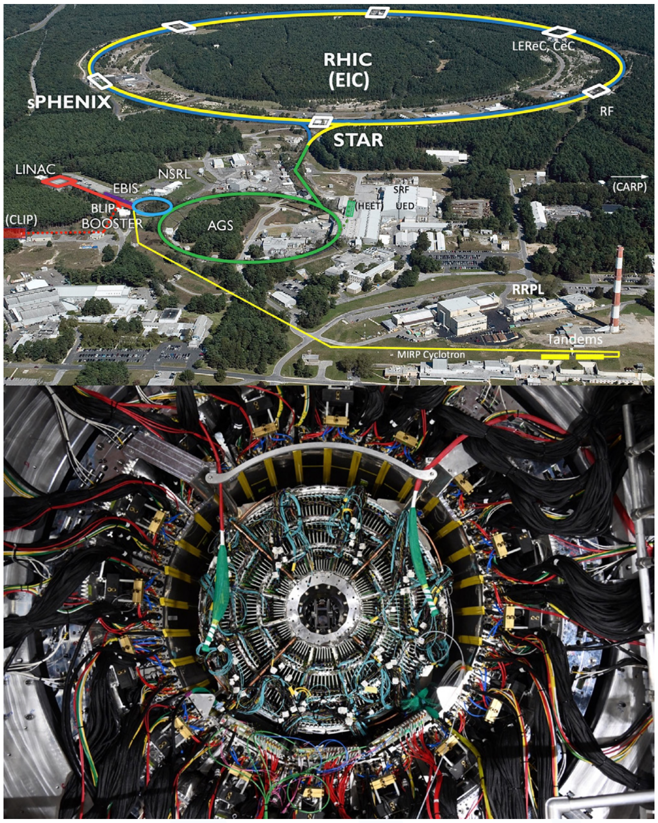


Figure 9.5. RHIC Accelerator Complex at Brookhaven National Laboratory. *(top) The layout of RHIC on the BNL site and an illustration of its two principal detectors. Also shown are the NASA Space Radiation Laboratory and Brookhaven Linac Isotope Producer (BLIP) facilities. (bottom) The sPHENIX detector. [42]*

Staff and the infrastructure for running RHIC and the future EIC also enable the operations of two other facilities that use particle beams and have broader impacts for science and society. One, the Brookhaven Linac Isotope Producer (BLIP), is part of DOE IP. BLIP scientists produce isotopes that are used for some industrial applications and to diagnose and treat diseases such as cancer. They also explore new isotopes and ways to combine isotopes with immunotherapies as well as methods to improve isotope production. The other facility is the NASA Space Radiation Laboratory (NSRL). NSRL produces beams that simulate the types of radiation that astronauts and their spacecraft would be exposed to on long-term spaceflights—for example during future missions to Mars. Scientists use NSRL to study how this radiation damages cells, DNA, and electronics so they can devise ways to protect future astronauts and sensitive equipment. Research at NSRL also helps scientists understand how radiation can cause cancer and how it can be used to treat cancer.

9.2.6. Future Facility: The Electron–Ion Collider

The EIC will be an innovative, large-scale particle accelerator facility capable of colliding high-energy beams of polarized electrons with heavy ions, polarized protons and polarized light ions. It is a joint endeavor between BNL and Jefferson Lab that will be built on the current site of RHIC. In December 2019, the EIC was launched as an official project of the US government when it was granted CD-0 status. Soon after, in June of 2021, the project was awarded CD-1, and it is on track to achieving CD-3A, permission to order long-lead items, by the end of 2023. Approval for the baseline performance (CD-2) and the start of construction (CD-3) are planned for 2025, with beam operations (CD-4) expected to commence in the early 2030s. The EIC will provide an intellectual and economic boon to the surrounding communities, both by attracting the top scientific minds in the world to BNL and by engaging a broad spectrum of creative and technical personnel. These jobs will range from engineers and technicians with expertise in cryogenics, electronics, and materials fabrication to publicists, administrators, and science writers.

To address the exciting scientific questions discussed in Chapter 3, the EIC design must provide five key features. The first is collisions of highly polarized (~70%) electron and proton beams, a capability that will be unique to the EIC. The second is the ability to collide electrons with a variety of ion beams, ranging from deuterons (a particle composed of a bound proton and neutron) to heavy nuclei such as gold, lead, and uranium. Third, the accelerator must be able to separately tune the energy of the electron and ion beams, providing center-of-mass energies for electron–proton collisions ranging from 29 to 140 GeV. Efficient collider operation requires high collision rates, which translates into electron–nucleon luminosities of 10^{33}–10^{34} cm^{-2} s^{-1}. Finally, the design must retain the possibility of more than one interaction region.

To achieve these goals, a host of techniques in accelerator physics and technology must be brought to bear. State-of-the-art superconducting radio frequency (RF) cavities are needed to efficiently accelerate high-intensity beams, and further specialized RF "crab" cavities beyond state of the art will rotate the beams as they collide to optimize their overlap and maximize the luminosity (Sidebar 10.1). Elaborate interaction region designs must squeeze two very different beams simultaneously into tiny spot sizes using advanced superconducting magnet designs. The hadron beams must be compressed in volume by sophisticated new beam-cooling techniques that involve subtle interactions with ancillary electron beams. Polarized beams require polarized particle sources, specialized magnets to control the spin orientation of the beam, and a further level of beam physics mastery to preserve the polarization through the acceleration process to the collisions. Polarized colliding stored beams have been achieved before only at the Hadron–Electron Ring Accelerator (HERA), in the form of polarized positrons or electrons on unpolarized protons, and at RHIC where both colliding proton beams were polarized. The development and implementation of these cutting-edge techniques will allow the United States to maintain leadership status in the field of accelerator physics and technology.

Shown schematically in Figure 9.6, the EIC will collide counter-circulating beams at two interaction regions, IR6 and IR8. DOE has committed to building a general-purpose, large-acceptance detector that can address the science case outlined in the 2018 NAS critical review and report, *An Assessment of the U.S. Based Electron-Ion Collider Science*. In 2020, the EIC Users Group launched a year-long effort to explore possible detector technologies and codify the detector requirements needed to address the NAS science case. The results of this study have been collected and published as the EIC Yellow Report. With the detector requirements defined, BNL and Jefferson Lab extended a call to the community in March 2021 for collaboration proposals for detector designs for both IP6 and IP8. A Detector Proposal Advisory Panel, an international committee of detector experts and theorists, was assembled to review the submitted proposals. The outcome of that competitive review process is the ePIC collaboration, which is in the process of finalizing the designs for the detector subsystems at IR6.

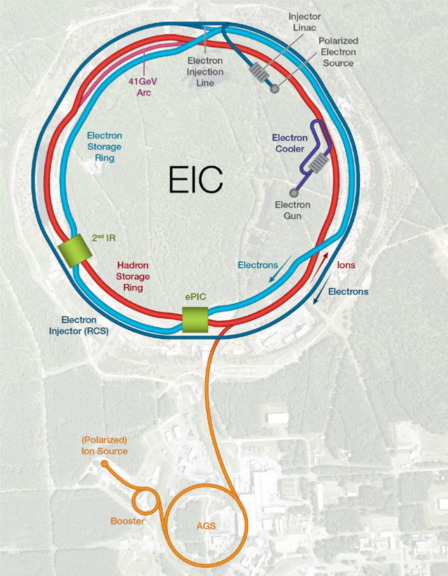


Figure 9.6. Planned EIC Facility [43].

To enable the full EIC physics program, the ePIC detector must provide complete kinematic coverage for particles emitted in the central, far-backward, and far-forward directions. Each of the central detector regions follow a similar particle detection concept, starting with high-precision vertex reconstruction and silicon-based trackers centered inside a 1.7 T superconducting solenoid. The magnetic field and tracking detectors provide momentum reconstruction for charged particles over a wide range of energies, up to 50 GeV. Cherenkov and TOF detectors, placed outside of the trackers, are used to identify and distinguish between different types of charged particles. The outside layer of the central detector consists of electromagnetic and hadronic calorimeters that are used to determine the energy of both charged and neutral scattered particles. In addition to the central detector, the far-backward and far-forward spectrometers provide beam monitoring and detect exclusive processes, including spectator nuclear fragments.

Historically, projects of similar scientific impact and scope were designed to include two or more complementary detectors, and the EIC community has emphasized the need for at least two detectors for many years. Multiple detectors will expand scientific opportunities, draw a more vivid and complete picture of the science, provide independent confirmation for discovery measurements, and mitigate potential risks when entering uncharted territories. A second detector would turn on several years after ePIC, and the EIC community will use this time to explore new and complementary detector technologies that may not have been employed in the project detector. The EIC Users Group is in the process of refining the science case for a second detector and is actively working to engage additional national and international resources for this effort.

9.3 ARUNA LABORATORIES

Low-energy particle accelerator facilities, which are mostly located at universities, provide important and unique beam and research capabilities for basic research and applications of nuclear physics. These facilities contribute significantly to forming the national infrastructure for stable and rare isotope beam capabilities for nuclear physics research in the United States. Around a decade ago, many of the university-based accelerator laboratories in the United States organized to form ARUNA.

ARUNA members include Florida State University (FSU), Hope College, James Madison University (JMU), Ohio University (OU), Texas A&M University (TAMU), Triangle Universities Nuclear Laboratory

(TUNL; Duke University, North Carolina Central University, North Carolina State University, University of North Carolina at Chapel Hill), Union College, University of Kentucky (UK), University of Massachusetts at Lowell (UML), University of Notre Dame (ND), University of Washington (UW), and Western Michigan University (Figure 9.7). In addition to providing a high level of hands-on training in every aspect of an experiment, the accelerator facilities at these institutions provide unique beam and research capabilities that are often not available elsewhere. These facilities add an element of agility to US low-energy nuclear physics research by offering flexibility in scheduling and quick response to research developments and challenges. Importantly, ARUNA facilities are cost-effective to operate, enabling beam time to be devoted to a project for a long duration as is often required in nuclear astrophysics, where cross sections are low, and in fundamental symmetries, where high statistics and extensive studies of systematics are required. The diversity of approaches provided by these laboratories is a critical asset of the field, and ARUNA laboratories provide a highly creative, flexible, stimulating, and supportive scientific environment with many opportunities for students to acquire the essential skills necessary for them to become a well-trained nuclear workforce. Scientists at ARUNA facilities pursue research in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications that build bridges to other research communities.

Figure 9.7. The unique ARUNA facilities are distributed throughout the country in 11 states: Florida, Kentucky, Indiana, Massachusetts, Michigan, New York, North Carolina, Ohio, Texas, Virginia, and Washington [44].

A range of unique capabilities for programs across the nuclear physics subfields are provided by the ARUNA laboratories and institutions: mono-energetic gamma beams (TUNL); mono-energetic neutron beams (UK, OU, TUNL, UML, ND); long-baseline neutron TOF spectroscopy (OU); high-intensity light-ion beams for nuclear astrophysics (ND, TAMU, TUNL); high-intensity heavy-ion beams for nuclear astrophysics (ND, TAMU); high-resolution magnetic spectrographs (FSU, ND, TUNL); the only high-resolution spectrometer at a cyclotron facility in North America (TAMU); world-leading trapping of helium-6 and neon-19 for precision beta-decay measurements (UW); an x-ray digital imager (JMU); and facilities to produce radioactive beams (FSU, ND, TAMU), including the world's only triple-solenoid separator (ND). In addition to these unique capabilities, several ARUNA laboratories and other university research groups (e.g., San Jose State University, Oregon State University, ND) pursue efforts in target fabrication and development to facilitate accelerator-based experiments and early career training in targetry. Examples of recent and ongoing significant ARUNA laboratory upgrades to beam and research capabilities since the last Long Range Plan are given here.

FSU hosts the John D. Fox Laboratory. This laboratory focuses on nuclear structure and astrophysics research, using a 9 MV tandem coupled to an 8 MV superconducting linac. In addition to housing a suite of detectors enabling nuclear spectroscopy of particles and gamma rays, the laboratory produces light in-flight radioactive beams with its Resonator Solenoid with Upscale Transmission (RESOLUT) facility. The injector system is currently being upgraded with a triton-ion beam source. This new beam capability, currently unavailable elsewhere, will create opportunities for measuring two-neutron transfer reactions. Also, a planned upgrade of additional cryostats to the superconducting linac will increase the achievable potential from 8 MV to 13 MV, enabling delivery of high-purity beams with nuclear masses up to $A \approx 50$.

OU's Edwards Accelerator Lab focuses on measurements using precision neutron time of flight. The facility has commissioned a new Alphatross high-intensity alpha ion source, as well as a fixed-angle short trajectory beamline for short flight-path neutron studies.

At the ND Institute for Structure and Nuclear Astrophysics, the new triple solenoid (TriSol) beamline was recently commissioned, producing in-flight beams with good emittance. The commissioning of a high-resolution split-pole spectrograph at the 11 MV tandem is planned, allowing for particle spectroscopy studies. In addition, a new neutron source has been installed for measuring neutron-induced cross sections. The facility hosts several tandem accelerators and a variety of experimental end stations for nuclear astrophysics, reactions, and structure research, as well as interdisciplinary programs involving biomechanics, materials analysis, and radiation chemistry. ND, in collaboration with the South Dakota School of Mines and Colorado School of Mines, operates the Compact Accelerator System for Performing Astrophysical Research (CASPAR), the only deep underground accelerator laboratory in the United States.

At TUNL, a DOE Center of Excellence, research programs address open questions in nuclear structure, reactions, astrophysics, and fundamental symmetries. Also addressed are broader questions of accelerator development, nuclear data, homeland security, and even biology. Several upgrades to the various facilities are completed, underway, or planned. The High-Intensity Gamma-Ray Source (HIγS) is the world's most intense Compton gamma-ray source, producing quasi-monoenergetic gammas from 1 to 100 MeV. Recent developments have provided large gains in gamma intensity and access to gamma-ray beams with energies up to 120 MeV, significantly increasing the sensitivity of Compton scattering to the nucleon polarizabilities. Furthermore, a plan has been developed to upgrade the electron injector for enhanced performance and reliability as part of an ongoing effort to modernize accelerator systems used in student training. At TUNL, a new 2 MV Singletron accelerator was recently installed in the Laboratory for Experimental Nuclear Astrophysics. It features intense beams of hydrogen and helium, which can be pulsed to provide background rejection for experiments, rivaling underground measurements. The injector system in the tandem accelerator at TUNL is being upgraded with two new ion sources, boosting the intensity for both light and heavy ions.

The TAMU Cyclotron Institute, a DOE Center of Excellence, operates two cyclotrons—the K150 (room temperature) and the K500 (superconducting)—that provide a wide variety of charged-particle beams to enable broad research programs in nuclear reactions, nuclear structure, nuclear astrophysics, and fundamental symmetries. TAMU also hosts a radiation effects laboratory and a precision decay counting station for efforts in materials research, homeland security, and nuclear data. Several recent upgrades will substantially increase ion beam availability and intensities, creating opportunities in basic research along with medical isotope and in-flight rare isotope beam production. A Light Ion Guide Separator for TAMU's Rare Isotope Beams (LSTAR) for the K150 rare-isotope beams is being designed to transport and purify radioactive ion beams, enabling high-precision measurements of fundamental symmetries. The TAMU Cyclotron Facility also hosts the Radiation Effects Facility (Sidebar 9.3) for testing the effects of ionizing radiation on electronic systems both in vacuum and in air.

These unique facilities, funded through the base nuclear physics research program, play a central role across the entire nuclear physics community through their research infrastructure and the expertise of the researchers that sustain a wide range of scientific research and technology development projects. At these facilities new ideas are explored, cross pollinated, and gain traction in the broader community. The connection of research at the ARUNA facilities to the goals of the national community allows for a synergy of scales, in which new developments can be pursued at ARUNA facilities, which in turn lead to new opportunities at the national user facilities. Furthermore, by their nature, these valuable university-based laboratories offer opportunities for workforce training in all aspects of an experiment: design, engineering, data analysis, publication, and leadership. ARUNA leadership in providing rigorous, hands-on training to the next generation of nuclear physicists and STEM leaders is highlighted in Sidebar 9.2.

9.4 NEUTRON FACILITIES FOR NUCLEAR PHYSICS EXPERIMENTS

Experimental programs in the United States that use cold and ultracold neutrons for basic nuclear physics research are conducted at three major facilities: the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source (SNS) at ORNL, the ultracold neutron (UCN) facility at LANL and the NIST Center for Neutron Research (NCNR) on the NIST campus in Gaithersburg, Maryland. In contrast to other nuclear physics laboratories in the United States, these installations receive no facility-level support from nuclear physics funding agencies. Instead, such support is provided gratis by facilities whose programmatic priorities lie outside basic nuclear physics and/or by individual experiments. As a result, facility-level support tends to be minimal and lacks continuity.

At SNS, funded by the DOE SC Basic Energy Sciences program, a 1.4 MW proton accelerator and mercury spallation target provide the world's most intense source of pulsed cold neutrons to 20 instruments used for condensed matter physics and materials science research. The FNPB, commissioned in 2010, is the only SNS beamline dedicated to basic nuclear physics experiments using cold neutrons. Important previous results include hadronic parity violation in neutron capture on hydrogen and helium-3. The neutron "a" and "b" (Nab) unpolarized neutron decay experiment is now commissioning on FNPB. When complete, it will be followed by the neutron electric dipole moment experiment at SNS (nEDM@SNS). The FNPB operation is currently supported by DOE NP on a per-experiment basis, but the FNPB facility receives no direct support. As the operation of the nEDM@SNS apparatus ramps up and extends into the 2030s, the team estimates that operational support requirements will roughly double.

The LANL UCN facility employs spallation neutrons with a superthermal solid deuterium converter to deliver high UCN density to precision neutron physics experiments such as UCNA (beta asymmetry), UCNτ (neutron lifetime), and the upcoming UCNProbe (neutron lifetime) and LANL nEDM (electric dipole moment). It is currently the only UCN source in North America with an active experimental program, but it is not currently supported as a user facility. The cost of operating the UCN source has been included within the operational budgets of individual experiments. Therefore, the frequent requests for beam time from outside users (both from inside and outside the United States) have been impossible to accommodate. It has also been difficult to operate the source in a stable manner to support all the approved experiments, execute adequate maintenance, and develop technical improvements. Additional facility support

Sidebar 9.2 Specialized Research Facilities Across the Country

The breadth of nuclear physics requires a portfolio of facilities covering a wide range of capabilities to support world-leading measurements. These facilities include smaller university-based accelerators, specialized neutron sources, and even underground laboratories.

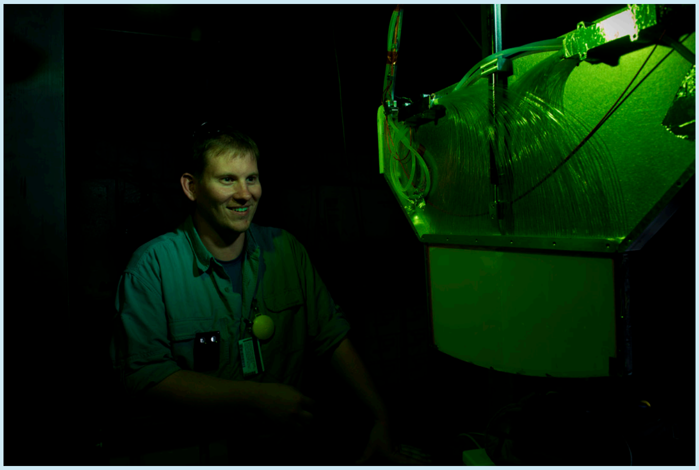
These facilities are distributed throughout the United States. They have a central role in educating the next generation of scientists and in training engineers and technicians by providing hands-on research opportunities.

Clover Array with HIγS accelerator at TUNL [S69]

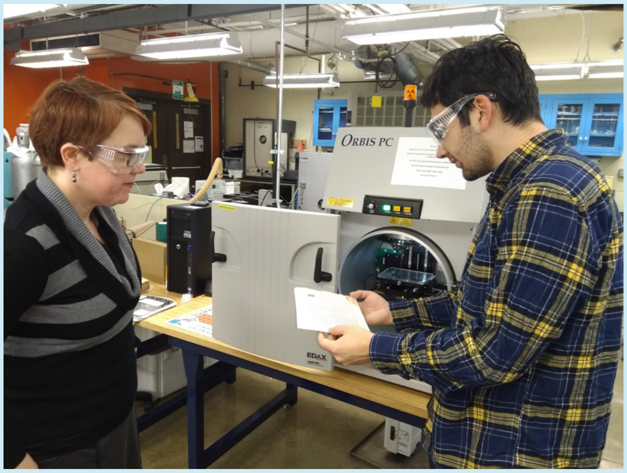
Sanford Underground Research Facility [S70]

Tandem Control Room at TUNL [S71]

Beyond workforce development, these facilities harness unique local detector systems and build new high-tech capabilities across the country. This portfolio of small- to medium-sized specialized facilities are critical for nuclear physics and are a key part of the national scientific infrastructure.



Fiber-optics tests at Ultracold Neutron Source (LANL) [S72]



Materials characterization at Notre Dame [S73] by funding agencies is needed for the success of ongoing and future experiments.

The NCNR is operated by the US Department of Commerce as a neutron user facility for the broad US research community, including industry and academia. A 20 MW research reactor and liquid hydrogen cold source provide the highest integrated cold neutron flux beams in the United States to a suite of instruments mostly dedicated to condensed matter physics and materials science research. The NIST Neutron Physics group operates several beamlines used by the nuclear physics community but has no provision in its budget to support beam operations for beam users. It can and does use its group expertise and research budget to support experiments, but this support can only be provided on a limited discretionary basis, especially because costs are increasing. During the past 30 years, major NSF- and DOE-funded nuclear physics experiments in neutron decay (e.g., beam lifetime, emiT, RDK, aCORN), hadronic parity violation, and neutron interferometry have operated and obtained important results at the NCNR. A new beam lifetime experiment—BL3—intended to help resolve the beam–bottle neutron lifetime discrepancy, is under construction.

Cold and ultracold neutron experiments address important problems in basic nuclear physics and enable unique precision tests of the Standard Model. These diverse, small- to midscale experiments require neutron facilities that are currently available only at nonnuclear physics laboratories, leading to key shortfalls in facility-level support. An improved model whereby modest funding from nuclear agencies would support a dedicated beamline scientist, local R&D, and engineering/technical services at each of these three facilities would enhance performance; reduce risk; ensure continued operation for the current and planned DOE- and NSF-sponsored experiments operating at them; provide continuity between experiments; and support R&D that will allow a full realization of discovery science, applications, and workforce development.

9.5 UNDERGROUND AND SUPPORTING LOW-BACKGROUND FACILITIES

The surface of the earth is constantly being bombarded by particles from showers produced when cosmic ray particles hit the upper atmosphere. For this reason, experiments designed to measure rare events must move underground. The highest profile of these experiments are the searches for neutrinoless double beta decay. These experiments are now looking for approximately one decay event per year in 1 ton of instrumented isotope. Underground facilities are critical for US leadership in such science, and this space is highly coveted because of the worldwide shortage of quality underground facilities.

The premier underground laboratory in the United States is Sanford Underground Research Facility (SURF) in Lead, South Dakota, in the Homestake gold mine. The mine was host to Ray Davis' Nobel prize–winning solar neutrino experiment. With the donation of the mine to South Dakota in 2006, the mine started the transition to a modern underground laboratory. The flagship nuclear physics project, the Majorana Demonstrator, was one of the first projects to be hosted at SURF. Significant infrastructure was put in place to host the project, including underground clean rooms, a clean-room-based machine shop, and facilities to produce ultralow-background electroformed copper.

The space at SURF to host nuclear physics experiments is limited. For this reason, plans are underway to locate the ton-scale neutrinoless double beta decay experiments at Canada's Sudbury Neutrino Observatory Laboratory (SNOLAB) and Italy's Laboratori Nationali del Gran Sasso (LNGS). Both have hosted several generations of large underground experiments and have significant infrastructure in place to successfully mount these experiments. As SURF continues to expand, it would be suited to host the next generation of neutrinoless double beta decay experiment here in the United States.

Once experiments move to one of these underground facilities, backgrounds caused by the natural abundance of uranium, thorium, and other unstable isotopes can swamp the rare signals. During the last half century, this community has developed a suite of screening and handling techniques to reduce these backgrounds at the corresponding facilities. For screening, the main facilities are those doing inductively coupled plasma mass spectrometry (ICP-MS) and low-background germanium counting. ICP-MS is done on the surface at very specialized chemistry-focused facilities. Germanium counting can be done at shallow sites but benefits from deep sites such as SURF. In support of the Majorana Demonstrator, DOE NP funded the development of extensive facilities at Pacific Northwest National Laboratory for low-background screening, including a shallow underground site and world-leading ICP-MS capabilities.

The facilities to house experiments underground and supporting low-background screening and handling are critical to enabling this type of nuclear physics experiment. However, these techniques are becoming important for a wider array of measurements as quantum sensing pushes the bounds of what can be measured. It has already been shown that the coherence time of superconducting qbits for quantum computing are sensitive to both cosmogenic and radioactive backgrounds. A host of qbit systems are now being deployed at underground facilities and are using low-background screening and handling facilities for the construction of their supporting infrastructure. This type of facility is increasingly needed to support US leadership across many disciplines.

9.6 COMPUTATIONAL FACILITIES

Computing and computational science have proven essential to achieve the scientific goals of the nuclear physics community as outlined in the Long Range Plan. They have enabled state-of-the-art calculations, simulations, and analyses for experimental and theoretical nuclear physics, accelerator beam physics and operations, and astrophysical observations. The advance of artificial intelligence (AI) and machine learning (ML) enables new capabilities to exploit patterns in data, accelerate calculations, and automate the design and operation of complex systems. Nuclear physics benefits from programs and partnerships to support high-performance computing (HPC) and AI/ML needs. That ecosystem supports cutting-edge developments and builds a multidisciplinary workforce and cross disciplinary collaborations.

The nuclear physics community benefits from a wide range of computational resources from national HPC centers and HPC or high-throughput computing resources at DOE laboratories as well as local clusters and workstations at universities and laboratories. The nuclear physics theoretical program has demonstrated over several decades of efforts that lattice QCD is an unmatched tool for understanding strong interaction physics ranging from the partonic structure of nucleons to the QCD phase diagram. Lattice QCD is, at its core, an HPC endeavor. Even the simplest calculations require significant time allocations on the world's largest machines. Lattice QCD is one of the critical applications selected for designing and benchmarking the exascale machines, for example, the Frontier supercomputer at the Oak Ridge Leadership Computing Facility. The need for computing resources scales exponentially with lighter quark mass, lattice spacing, and number of nucleons. The dedicated USQCD hardware located at Fermilab, BNL, and Jefferson Lab is an essential component for analysis.

Access to computing resources will advance our understanding of nuclear phenomena by targeting predictive capabilities in the structure and reactions of light nuclei and few-nucleon systems, precision calculations of nuclear matrix elements for fundamental symmetries, neutrino and electron interactions in nuclei, properties of nuclei and nuclear matter, properties of fission, and detailed models of nucleosynthesis sites. These capabilities allow predictions of critical nuclei relevant to ATLAS, FRIB, and other experimental activities worldwide and guide state-of-the-art updates to evaluated nuclear data libraries. The volume of data expected from experimental nuclear physics research in the next 20 years will require new data management and storage approaches, and the increased interconnection between computing facilities raises additional technical and social challenges. The DOE initiative toward an integrated research infrastructure is an opportunity for the nuclear physics community to establish a sustainable, scalable, and collaborative infrastructure that addresses common challenges, such as cyber security, federated access, and data management. Importantly for integrated research infrastructure design, nuclear physics is an integrative science in which knowledge is gained from the interplay of experimental results and theory. Adhering to findable, accessible, interoperable, and reusable data principles will ensure data availability and usability for multiple analyses. Emerging technologies are opening exciting opportunities. Quantum computing (QC), the large information capacity of qubits, and their inherent quantum mechanical nature hold the potential for addressing long-unsolved challenges in our understanding of large and strongly entangled quantum systems (Sidebar 3.6).

9.7 ACCELERATOR R&D

To maintain its position as a leader in nuclear physics, the United States must have state-of the-art accelerator technologies while working to develop new technologies. Accelerator R&D should focus on beam physics of intense beams, beam control and advanced beam tuning techniques, new sources for intense polarized and unpolarized electron and ion beams, and superconducting radio frequency (SRF) technology to tackle beam intensity and beam quality challenges. Although beam energy is not a challenge for nuclear physics facilities, it is important to develop more efficient and cost-effective accelerators, a goal shared with the high-energy physics community. High driver beam intensities of the new generation of high-power rare-isotope accelerator facilities such as FRIB are essential to address fundamental questions about the inner workings of nuclei and the formation of the heavy elements. The intensity and emittance of beams are critical factors for accelerator capabilities, and they are limited by our understanding of collective effects and loss mechanisms. A complete understanding of these effects is necessary to overcome the beam intensity limitations and to increase beam intensity by orders of magnitude in the future. An area of application for such improvements is the energy recovery linac technology, which can be used as an electron injector or high-energy electron cooler for hadron beams.

Preserving a high level of spin polarization in present accelerators and for EIC is essential and will build on RHIC's successful polarized beam program. To ensure good beam quality, significant beam control capabilities are necessary to match the beam distribution specifically to the experimental or application needs. Developing virtual particle accelerators will provide more predictive tools that enable fast computer modeling of particle beams and accelerators at unprecedented levels of accuracy and completeness. It will accelerate the realization of required beam intensity and quality for nuclear physics flagship facilities. The EIC design and construction requires beam physics techniques and tools such as

Sidebar 9.3 Electronics Radiation Effects

Radiation is a constant concern for people who travel to space and for the spacecraft that transport them. Thus, electrical parts must be tested to determine how they stand up to radiation, particularly as new electronics with technological advances and smaller components raise new challenges.

Figure 1. Students helping to explain aspects of hardware and software necessary to studying single event effects at the TAMU radiation effects bootcamp [S74-75].

Radiation testing on electronics is important to determine the presence and characteristics of so-called single-event effects. The testing determines whether these events are destructive, whether they are voltage or temperature dependent, and their magnitude. During the past 3 years, nearly 100 electronic components of the Crew Dragon capsule were tested at the Texas A&M University Cyclotron Institute Single-Event Effects beamline (Figure 1). The NASA Space Radiation Laboratory at Brookhaven National Laboratory, the 88-Inch Cyclotron at LBNL, and the Facility for Rare Isotope Beams also host space-effects beamlines (Figure 2). Argonne National Laboratory's ATLAS facility has a new beamline dedicated to understanding radiation effects on materials.

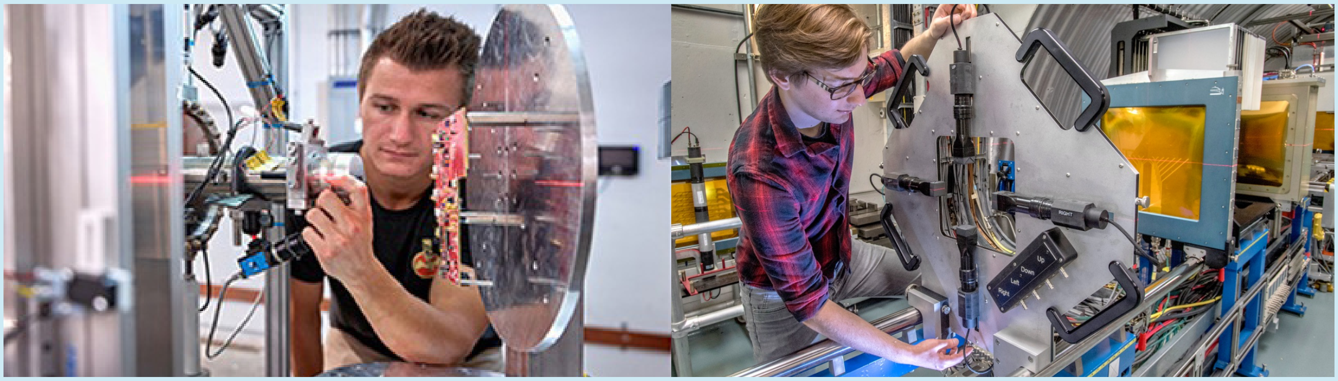


Figure 2. Staff working at the space radiation laboratories at FRIB [S76] (left) and BNL [S77] (right).

generation and acceleration of polarized beams, AI/ML-based tune-ups, managing electron–proton (ion) beam–beam effects with a crossing angle and superconducting crab cavities. Nonlinearities that limit the dynamic aperture, collective effects in the electron storage ring, and strong hadron cooling are also important topics to be addressed.

RF cavities and magnets made from conventional and newer high-temperature superconducting materials, as well as permanent magnets, are R&D topics in both the nuclear and particle physics communities. Progress in SRF cavity design in terms of high *Q*-values, high gradients, and higher-order mode damping capabilities along with new magnet designs will be critical for the future of FRIB (i.e., FRIB400), the EIC, and the operation of ATLAS and CEBAF. Argonne's Accelerator Development and Test Facility is key to the maintenance, development, and operation of such state-of-the-art devices. A higher beam energy for the FRIB driver accelerator will provide a significant increase in rare isotope production and isotope separation abilities. The staged upgrade plan for CEBAF foresees a first phase to establish intense polarized positron beam capability at 12 GeV, allowing for new measurements in nucleon tomography and providing precision extraction of contributions from higher order electromagnetic processes. The nontrivial operation with positron beams (polarized and unpolarized) will open a new area of study for CEBAF in the future. The subsequent phase is an energy upgrade of CEBAF to more than 20 GeV. Recently, the Cornell Brookhaven Electron Test Accelerator (CBETA) facility demonstrated eight-pass recirculation of an electron beam with energy recovery employing arcs of fixed-field alternating gradient magnets. This exciting new technology could enable a cost-effective method to double the energy of CEBAF, allowing wider kinematic reach for nucleon femtography studies in the existing tunnels and with no new cryomodules required.

CARIBU allows ATLAS to produce world-unique beams of neutron-rich rare isotopes. However, the source used, californium-252, has a 2.65 year half-life, requiring a challenging replacement every three years to maintain high beam intensities. A new system, nuCARIBU, provides neutron-induced fission on actinide foils to overcome these issues. A Best Cyclotron (6 MeV proton beam at 0.5 mA) was chosen to deliver protons to a lithium-7 target to produce neutrons, which are moderated to thermal energies to induce fission in an actinide foil, providing neutron-rich fission products. An ongoing upgrade program of the facility, the ATLAS Multi-User Upgrade, will enable the delivery of ATLAS beams to more than one experiment at a time, thereby significantly increasing the effective hours of beam on target. The proposed upgrade will take advantage of the continuous-wave nature of ATLAS and the pulsed nature of the EBIS charge breeder to simultaneously accelerate two beams with very close mass-to-charge ratios—one stable from the existing ECR ion source and one radioactive from the EBIS charge breeder—requiring advanced beam control in the ATLAS facility.

9.8 DETECTOR R&D

Nuclear physics detection techniques need to cover a broad range of energies and sensitivities, from thousands to tens of billions of electronvolts and from millions of events every second to single events every decade. Therefore, nuclear physics often places varied and unique demands on detector research and development. Such technologies developed often have many societal benefits, so investment and innovations in detector technologies are essential to maintain US leadership in nuclear physics. An open and sustainable nuclear physics detector R&D program will ensure that state-of-the-art and beyond detector technologies are available to enable discoveries in nuclear science and applications with broad societal benefits. Many such efforts benefit from collaboration with industry, through programs such as the DOE and NSF Small Business Innovation Research and Small Business Technology Transfer programs. A large fraction of the community is involved in these efforts where new, small-size, and large-scale instruments are being conceived, designed, and constructed. In many instances, these efforts provide invaluable hands-on experience to students (undergraduate and graduate) and postdocs, thereby contributing significantly to the education of the nuclear science workforce of the future.

In low-energy, accelerator-based nuclear physics research, the broad range of necessary measurements and techniques drives a need for an equally broad range of detector technologies. Well proven technologies such as semiconductor- or scintillator-based detectors operate alongside novel quantum-tunneling devices. Many detector systems are built for a specific facility, whereas others can be transported to an experiment anywhere in the world. Since the last Long Range Plan, a major success of this effort has been the Gamma-Ray Energy Tracking In-Beam Nuclear Array (GRETINA), which is on track to become GRETA. GRETINA was built on the development of cutting-edge coaxial, electrically segmented, high-purity germanium detector modules and was designed to incorporate ancillary detector systems. Also since the last Long Range Plan, FRIB has gained the community-driven FDSi, a novel combination of existing detector technologies to provide discrete and calorimetric spectroscopy of the first FRIB beams. The new Argonne Tandem Hall Laser Beamline for Atom and Ion Spectroscopy (ATLANTIS) setup for nuCARIBU builds on the state of the art for laser ion trapping. Gammasphere has been refurbished with cutting-edge digital electronics that enable improved sensitivity and rate capabilities. Elsewhere in the community, new developments in TPCs and other gas-filled detectors, custom liquid scintillator chemistry, and novel combinations of existing detector technologies, especially when instrumented with digital electronics, are pushing the limits of detection in fields ranging from astrophysics to superheavy elements. The ARUNA laboratories also drive detector development with novel detector arrays such as the Detector Array for Photons, Protons, and Exotic Residues (DAPPER) at TAMU, which is based on fast inorganic scintillator technology; the fInternal conveRsion Electron Ball (fIREBall) spectrometer at ND (Sidebar 4.2), or the exceptional neutron–gamma pulse shape discrimination of RESONEUT, the neutron array at FSU's RESOLUT.

In the coming decade, the community looks forward to the full discovery potential of FRIB, at the limits of nuclear existence, to be facilitated by the novel FDS, the HRS, and ISLA. Advances will also be made at the limits of count rate and sensitivity by using novel data acquisition strategies and ML-based pulse-shape analyses. The application of quantum sensing technologies to low-energy nuclear physics is another exciting avenue for detector development in the next Long Range Plan period. Currently deployed technologies involve instruments sensitive to low-energy transitions, such as superconducting tunnel junctions and transition-edge sensors. Looking forward, entanglement in many-body systems can be used as a tool to reduce fluctuations below the standard quantum limit.

At the higher energies of accelerators probing the partonic structure of the nucleon and nuclei, detector requirements can be open ended. In January 2011, BNL, Jefferson Lab, and DOE NP created a generic detector R&D program to address the scientific requirements for measurements at an EIC. Open to the international EIC community, many of the supported projects developed technologies that are now integral parts of existing detector concepts. In 2022, this program was updated to focus on potential upgrades to the EIC ePIC detector and on new technologies. One such example is micropattern gaseous detectors (MPGDs), which are rapidly becoming the choice for cost-effective instrumentation of large-area detection and for continuous tracking of charged particles with minimal detector material. More than 50 US research institutions are involved in MPGD development or activities for experiments in different fields of physics that would benefit directly from a novel US-based MPGD facility. Several of these institutions are members of the European Organization for Nuclear Research (CERN)-based RD51 collaboration, which focuses on the advancement of MPGD technologies. Although the US institutions have benefitted from the facilities at CERN, the community is growing swiftly and no such facility in the United States can accommodate this need. A facility with similar capabilities has been proposed to be located at Jefferson Lab to support the US-based innovation in this novel detector technology and US researchers. It will strongly benefit future high-profile experiments at Jefferson Lab, the tracking system for the detectors of the EIC, and more and will be an asset to the nation's scientific community. Continued support of detector R&D for the high-energy experiments at the LHC both draws from and contributes to the technology needed at Jefferson Lab, RHIC, and soon the EIC.

Looking to the future, many opportunities for detector R&D in the near and intermediate term exist, and examples include superconducting nanowire particle detectors that are being developed for nuclear physics applications for the EIC and experiments at Jefferson Lab. Furthermore, excitingly, cross-cutting development efforts with advanced computing are conceived to facilitate self-driving detector systems: ePIC at EIC or SoLID at Jefferson Lab are candidates for initial large-scale deployment of such a concept. Here, a combination of heterogeneous computing, AI, ML, advanced computing, and streaming readout is anticipated to reduce the time from data collection to publication and improve efficiency of experimental operations.

Considerable effort in recent years has gone into developing cutting-edge detector technologies for rare decay searches such as neutrinoless double beta decay and other tests of fundamental symmetries. In addition to the strict requirements on isotopic enrichment, these low-background searches rely on both active and passive shielding to allow unambiguous identification of the signals of interest. For example, scintillator materials that operate at cryogenic temperatures are being developed to provide an active veto of cosmogenic signals in the liquid argon surrounding the main germanium-based detectors of LEGEND. Another background-reduction technique is barium tagging in noble gas/liquid detectors such as those planned for a next-generation nEXO. Neutrino mass searches also rely on substantial instrument development, such as the microwave cavity at low magnetic fields required for Project 8. Quantum sensors are already in use in neutrinoless double beta decay, neutrino mass measurements, sterile neutrino searches, precision tests of fundamental symmetries, permanent electric dipole moment searches, and as probes of rare and exotic processes. Their targeted use in nuclear physics continues to grow.

9.9 INTERNATIONAL FACILITIES

Nuclear physics research is intrinsically global, and increasingly requires international collaborations. Foreign governments have been investing significantly in nuclear physics facilities outside the US since the 2015 Long Range Plan, and they will continue to do so with upgrades and new facilities. The US participation in international facilities provides significant opportunities and complements domestic capabilities for US nuclear physicists. International facilities are pictured in Figure 9.8.

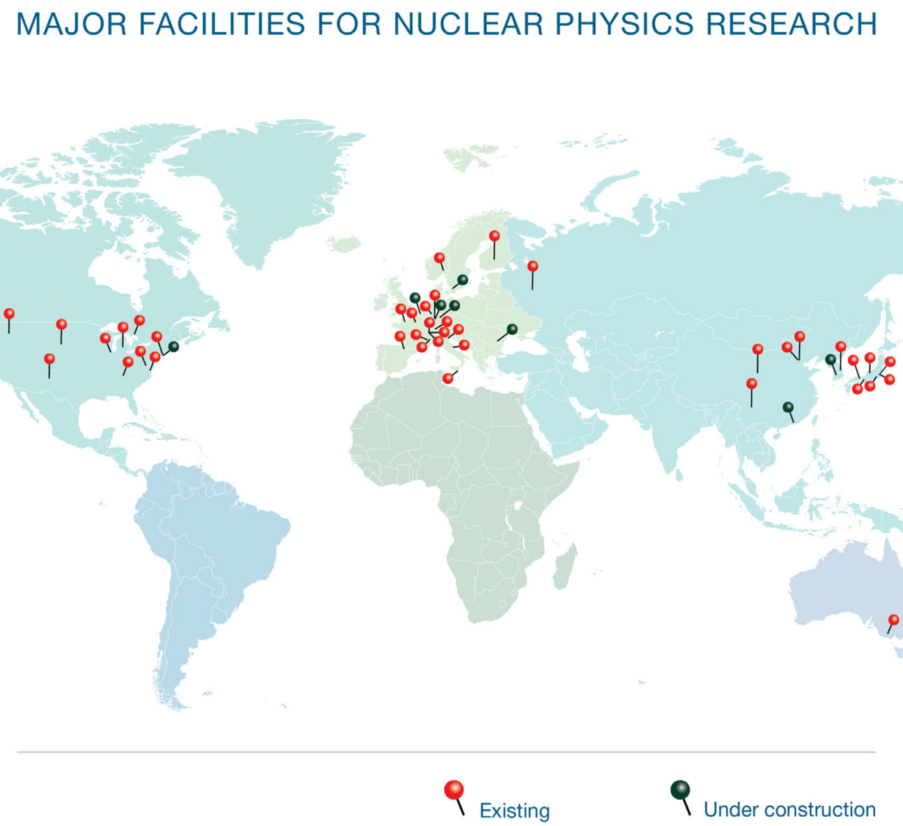


__Figure 9.8. International nuclear physics research facilities.__ Map indicating the site of the main nuclear physics facilities worldwide, either existing (red) or under construction (black) [45].

TRIUMF—Canada's Particle Accelerator Centre—operates the Isotope and Accelerator (ISAC) complex. Several US groups are involved in electroweak precision experiments at ISAC, for instance the TRINAT magneto-optical trap, the DOE NP funded Francium Trapping Facility, and the Beryllium Electron Capture in Superconducting Tunnel Junctions Experiment (Sidebar 6.4). The completion of the Advanced Rare Isotope Laboratory (ARIEL) is expected in 2026. ARIEL, the only purpose-built multiuser rare isotope facility that will triple the available beam time, will stay the world's most powerful isotope separation online (ISOL) complex with highest low- and medium-energy rare ion beam intensities of selected elements for the period of this Long Range Plan. The ISOL facility at TRIUMF is complemented by its European counterparts: the Isotope Mass Separator On-Line (ISOLDE) facility at CERN and SPIRAL1 at the National Large Heavy Ion Accelerator (GANIL). At ISOLDE, a wide variety of more than 1,000 radionuclides can be produced and delivered to different experimental end stations at the ISOLDE beamlines. Recent US involvement has been in the high-precision laser spectroscopy program in pursuit of charge radii, moments, and electronic structures of rare isotopes and molecules, reaction studies with the ISOLDE solenoid spectrometer, and various spectroscopy studies following decays or reactions. The five-cyclotron complex at GANIL delivers stable beams with energies between 1 and 95 MeV/u, fragmentation beams up to about 50 MeV/u, and reaccelerated ISOL beams (SPIRAL1) from 1.2 to 25 MeV/u to a wide variety of experimental end stations. Most recently, US researchers have exploited the opportunities afforded at GANIL for reaction studies and are involved in the S3 separator for the new SPIRAL2 facility. University of Jyväskylä Department of Physics Accelerator Laboratory (JFYL) and two of the Italian National Institute of Nuclear Physics laboratories provide accelerated stable beams at energies between 5 and 10 MeV/u. JFYL operates a K130 isochronous cyclotron, which can deliver a large variety of heavy- and light-ion stable beams. US researchers are collaborating at the facility in searches for heavy proton emitters and studies of excited states in the heaviest nuclei. The Legnaro National Laboratory (Italy) center houses a system of ion sources, a tandem and superconducting linear accelerator, and target stations dedicated to basic and applied nuclear physics research. US researchers have recently leveraged the facility to study nuclear shape coexistence by using Coulomb excitation techniques and are involved in a planned upgrade of the radioactive-ion beam production (SPES project). The Institute of Physical and Chemical Research (RIKEN; Japan) Rare Ion Beam Factory (RIBF) has been the world's most powerful rare isotope beam facility based on fragmentation for more than a decade and will only be eclipsed in beam intensity once FRIB's ongoing power ramp-up crosses the threshold of 10–15 kW. At the heart of the facility is a coupled-cyclotron accelerator complex and various experimental end stations. Ion beams across the entire atomic mass range can be accelerated typically up to energies of 345 MeV/u. The beams are delivered to the production target of the Superconducting Radioactive Isotope Beam Separator (BigRIPS), which produces various fast rare-isotope beams. Recent US involvement has been in programs that use the produced rare isotopes for decay spectroscopy (e.g., the beta-delayed neutrons at RIKEN [BRIKEN] campaign, Sidebar 4.1) for new isotope discoveries, for invariant mass spectroscopy of neutron-unbound states at the Superconducting Analyzer for Multi-Particles from Radioisotope Beams (SAMURAI) facility, and for in-beam gamma-ray spectroscopy at the Zero-Degree spectrometer. Another important operational scheme is the direct use of the intense beams from the linac injectors—RILAC or RILAC2—for heavy-ion fusion reactions in pursuit of superheavy element formation. In the future, RIBF plans to add the two charge stripper rings to increase the beam intensity by a factor of 20.

The Japan Proton Accelerator Research Complex (J-PARC) is Japan's leading accelerator facility. J-PARC has cascaded proton accelerators, including the 400 MeV linear accelerator, the 3 GeV rapid cycling synchrotron and the main ring operated at 30 GeV. At the J-PARC Neutrino Facility, neutrino and antineutrino beams produced at J-PARC are sent to Super-Kamiokande located about 295 km to the west. The research topics at the Neutrino Facility include QCD-related physics such as neutrino–nucleus interactions. The Hadron Experimental Facility is a unique experimental complex that uses secondary beams to perform precision measurements on hyper-nuclear spectroscopy, hyperon–nucleon scattering, kaonic nuclei, and other topics of interest in QCD. J-PARC also houses a vibrant fundamental symmetries physics program that is searching for the nEDM and a neutron lifetime measurement. The Belle II experiment at SuperKEKB, an asymmetric energy electron–positron Super B factory located in Japan, will play an important and complementary role in the study of QCD alongside experiments involving hadron beams and/or hadron targets, as demonstrated by the previous Belle experiment at the High-Energy Accelerator Research Organization (KEK; Japan), the BaBar experiment at SLAC, and the ongoing BES-III experiment at BEPC II in China. The large Belle II dataset anticipated will enable the precise determination of complex correlations in the hadronization process, which are necessary for a detailed mapping of the QCD dynamics at play.

At the LHC, all four detectors (ALICE, ATLAS, CMS and LHCb) have significant heavy-ion programs with strong US participation. Before Run 3, the LHCb collaboration has completed the first of a series of detector upgrades, Upgrade 1. Before Run 4, LHCb will implement Upgrade 1b, which will include new tracking detectors. For Run 4, both ATLAS and CMS are planning major upgrades that will directly benefit the heavy-ion physics program. Both ATLAS and CMS will have upgraded trackers. CMS is also planning a new timing detector, which can make measurements with identified hadrons. ALICE has just completed several major upgrades, for which the US component of the ALICE collaboration (ALICE-USA) has made vital contributions to the new Inner Tracking System and Time Projection Chamber readout. ALICE-USA will now utilize these upgrades for a comprehensive physics program in the ALICE 2 phase that also provides a unique opportunity for hot and cold QCD studies between the expected times when RHIC discontinues collecting data in 2025 and when the EIC begins collecting data around 2035. ALICE-USA is one of the key proponents of the Forward Calorimeter (FoCal), which will collect data in Run 4. The development, installation, and operation of the FoCal will occur during the 2023 Long Range Plan timeframe and before the EIC begins collecting data. ALICE-USA fully supports the ALICE 3 detector, a next-generation detector that is designed to operate in Runs 5 and 6 (2035 and beyond). On the same timescale as the ALICE 3 detector, LHCb is planning Upgrade II to make measurements over the full centrality range of heavy-ion collisions for the first time.

The Facility for Antiproton and Ion Research (FAIR) in Europe, under construction at GSI Darmstadt, is a top-priority flagship facility for nuclear physics in Europe. US participation in the international collaboration of the Compressed Baryonic Matter experiment at this facility, driven by unprecedented beams from the superconducting heavy-ion synchrotron SIS100, will allow the US nuclear physics program to build on its successful exploration of the QCD phase diagram, use the expertise gained at RHIC to make complementary measurements, and contribute to achieving the scientific goals of the BES program. SIS100 and the FAIR Super Fragment Separator will enable the Nuclear Structure, Astrophysics, and Reactions (NUSTAR) program at FAIR. NUSTAR will have RIBs with the highest energies (>1 GeV/nucleon) and will provide opportunities for unique experiments not possible at other facilities. The University of Mainz in Germany is currently constructing the Mainz Energy Recovery Superconducting Accelerator (MESA): first electron beam is expected in 2024 for scientists to explore the limits of Standard Model physics. Among key experiments currently under development, the Mainz Gas Injection Target Experiment (MAGIX) is a multipurpose spectrometer for a precise determination of the proton charge radius and dark matter searches. MESA has grown from the expertise gained in operation of the Mainz Microtron accelerator, where US nuclear physicists are actively engaged in electron and photon scattering experiments. The Electron Stretcher Accelerator (ELSA) is operated by the University of Bonn in Germany. ELSA delivers a beam of polarized or unpolarized electrons with variable energies up to 3.5 GeV with main research topics in hadron physics.

US nuclear physicists are also actively conducting experiments in proton charge radius and fundamental symmetries studies at the Paul Scherrer Institut (PSI) in Switzerland and in hadron structure studies with the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) experiment at CERN, exploiting unique beam capabilities not available in the United States. International facilities are also critical to efforts in fundamental symmetries, in particular the search for neutrinoless double beta decay. Two main laboratories will provide the locations necessary for these low-background, rare-event searches: SNOLAB in Sudbury, Ontario, Canada, and LNGS near L'Aquila, Italy. SNOLAB is a world-class science facility located deep underground in the operational Vale Creighton nickel mine, near Sudbury, Ontario, in Canada. At a depth of 2 km, SNOLAB is the deepest cleanest laboratory in the world. It is an expansion of the facilities constructed for the Sudbury Neutrino Observatory (SNO) solar neutrino experiment and has 5,000 m^2 of clean space underground for experiments and supporting infrastructure. A staff of over 100 support the science, providing business processes, engineering design, construction, installation, technical support, and operations. LNGS is the largest underground laboratory in the world devoted to neutrino, astroparticle physics and nuclear physics located between L'Aquila and Teramo, Italy.

One of the technologies discussed in Chapter 6 for neutrinoless double beta decay, CUPID, will be sited at LNGS; the nEXO detector will be hosted by SNOLAB. LEGEND-1000, the ton-scale germanium-based system, can be hosted by either laboratory.

Various experimental facilities in Asia are involved in all areas of experimental nuclear physics, including those under construction. These facilities include the new Yemilab underground laboratory and the Rare Isotope Accelerator Complex for Online Experiment (RAON) in Korea; the Stawell Underground Physics Laboratory (SUPL) in Australia; and the Jinping Underground Laboratory for Nuclear Astrophysics (JUNA) facility, the Beijing Radioactive Ion Beam Facility (BRIF), the Heavy Ion Accelerator Facility (HAIF), and CJPL-II Underground Laboratory in China. All these international facilities are shown in Figure 9.8.

10 INTERSECTIONS AND EMERGING TECHNOLOGIES

The pursuit of nuclear science drives innovation and new technologies with significant benefit for industry and numerous other research fields. The development of new research facilities and state-of-the-art experiments pushes the boundaries of accelerator and detector science, which leads to new technologies with broad medical and industrial applications. The complexity of nuclear physics research problems, such as quantum chromodynamics (QCD) simulations, ab initio methods for the nuclear many-body problem, physics beyond the Standard Model, and large-scale data analysis, forces innovation in numerous aspects of high-performance computing (HPC) and the development and adoption of methods in the emerging fields of artificial intelligence (AI), machine learning (ML), and quantum computing. The synergy with these emerging fields helps drive intersections and innovation and provides important opportunities to renew, broaden, and diversify the NP workforce. These mutually beneficial partnerships between NP and wider science communities must continue to grow and flourish in the following key areas:

- *Accelerator and Detector Technology*—Nuclear physics demands are met through innovation in accelerator and radiation detection technologies, which drive strong intersections with research sectors in electronics, machine learning, plasma physics, and materials science.

- *Quantum Sensing and Simulation*—Increasingly sensitive detectors for nuclear science require utilizing coherence and entanglement in emerging quantum technologies, and predictive capabilities for the properties and dynamics of nonequilibrium dense matter require quantum computation and simulation co-designed for nuclear physics.

- *Artificial Intelligence and Machine Learning*—The ongoing revolution in the field of AI/ML has already affected several aspects of nuclear physics, from nuclear theory to accelerator operation. To capitalize on this promise, a fast and effective funding model must be developed to bring the hardware and software resources as well as workforce training to individual researchers.

- *High-Performance Computing*—Advances in supercomputing technologies provide unprecedented opportunities for nuclear science, and investments in hardware and access must be accompanied by resources for capacity computing, data centers and connectivity, and the education of a skilled workforce.

The following sections expand on these key opportunities.

10.1 ACCELERATOR SCIENCE

Particle accelerators are an enabling technology for nuclear physics. Although accelerator technology was developed for basic physics applications, it has significant impact on medicine and industry. The need for unprecedented beam properties will pose challenges for established and new nuclear physics facilities. These challenges can be met by innovations that will require strong connections to other research fields.

A large effort is underway to ensure a high degree of electron beam polarization at the EIC. The strict requirements on the EIC polarimetry and the significant background owing to Bremsstrahlung and synchrotron radiation put stringent constraints on the choice of detectors and will need new solutions. Because of the high electron beam intensities, controlling synchrotron radiation is crucial for the design of the EIC beam optics. The EIC is different from prior facilities: synchrotron radiation in the forward region must be absorbed on the rear side of the interaction region as far as possible from the detector. The beams collide with a large crossing angle that demands new superconducting crab cavities to restore head-on collisions. Elaborate interaction region designs must squeeze the two very different beams simultaneously into tiny spot sizes using advanced superconducting magnet designs. The demands of the EIC accelerator complex push multiple aspects of accelerator science—including superconducting technologies, kicker systems, beam instrumentation, and interaction point integration—beyond the state of the art.

The demands from nuclear science accelerators in terms of beam properties require specific R&D on superconducting radio frequency (SRF) technologies, significantly advancing the state of the art (Sidebar 10.1). All major nuclear physics facilities have established R&D programs in these areas (Chapter 9). The EIC storage rings will require a suite of superconducting cavities that will have unprecedented performance parameters, and FRIB400 is based on the development of new superconducting cavities. Several types of superconducting cavities were investigated at FRIB, and the chosen design is optimal because it allows for a low dynamic heat load with high accelerating voltage.

Fruitful synergies with other communities go well beyond the boundaries of nuclear physics and should be further exploited. For instance, the European nuclear physics research institutes have strong links with networks such as the League of European Accelerator-Based Photon Sources (LEAPS) and the League of Advanced European Neutron Sources (LENS). These groups focus on R&D specific for materials used in accelerators as well as beam optics and detector components. The US nuclear physics community should also leverage common accelerator technology and methodology developments in the areas of cost-effective accelerators, targetry, particle sources, advanced beam physics, and beam controls (including ML).

Exciting opportunities exist for future subatomic physics research to affect other related research fields such as space exploration. NP accelerator facilities develop key technologies to investigate nuclear processes relevant to the harmful effects of cosmic radiation on satellite electronics and on astronauts, especially for deep-space exploration (Sidebar 9.3). Proton and ion beams produced in accelerator facilities currently provide the only means on Earth to realistically simulate the space radiation environment. At BNL, scientists from the NASA Space Radiation Laboratory use beams of ions from protons to thorium with energies from 50–1,500 MeV to simulate cosmic rays and assess the risks of space radiation to human space travelers and equipment. The LBNL 88-Inch Cyclotron hosts the Berkeley Accelerator Space Effects (BASE) Facility, which provides well-characterized particle beams that are used to study the effects particle radiation on microelectronics, optics, materials, and cells. The TAMU Cyclotron Institute employs the Radiation Effects Facility to provide beams of heavy ions and protons to study, test, and simulate the effects of ionizing radiation on electronic and biological systems.

The recent developments of ultrahigh-gradient accelerators based on dielectric wall or plasma wakefield acceleration will allow for more compact and cost-effective accelerators for nuclear physics and for applications. The intersection with the field of laser and plasma physics as well as with materials science should be strengthened to allow for the development of ultrahigh-gradient accelerator systems for new injectors (including positron production and injector systems) or accelerators for NP facilities that provide ultralow-emittance electron beams.

10.2 EMERGING EXPERIMENTAL TECHNOLOGIES AND DETECTOR INNOVATION

Novel and advanced experimental techniques that have been continuously developed across all the nuclear physics subfields drive innovation in a variety of radiation detection technologies. Requirements unique to nuclear physics drive detector technologies in new directions with respect to other fields.

Many opportunities for detector technology development in the near and intermediate term exist in the EIC design, construction, and science operations era. These opportunities can best be considered in detector functionality areas such as particle identification, calorimetry, tracking, and readout electronics, to address how R&D projects can enhance the performance of the EIC detectors. The detector requirements imposed by the rich physics program at the EIC are demanding and unique among collider detectors: hermetic coverage in tracking, high-quality calorimetry and particle identification capabilities within a wide pseudorapidity range, and substantial angular and momentum acceptance in the hadron-going direction. In the electron-going direction, electromagnetic calorimetry providing high precision and hermetic detection of the scattered electron is required. Precision measurements need high momentum resolution, high efficiency, electron and hadron particle identification, and detector components with low material budget (Chapter 3). Examples of such detector opportunities include material minimization in a possible all-silicon tracker, particle identification reach at midrapidity and at higher momenta, cost-effective photo-sensors for readout of particle identification detectors such as large-area picosecond photo-detectors, and hadronic calorimetry technologies such as the tungsten scintillating fiber (W/SciFi) calorimeter and novel scintillating materials. The need for dedicated detector R&D will remain critical for reaching the EIC science goals, and broad detector R&D funding would benefit the EIC and the entire NP portfolio.

New experimental technologies in nuclear science are also being driven by fundamental-symmetries research, which for decades has provided among the most sensitive searches for physics beyond the Standard Model and thus powerful tools in probing the fundamental nature of the universe. Example innovations include the introduction of ion and atom trapping in the 1990s and, more recently, quantum sensing in nuclear physics (Chapter 6; Sidebar 6.4).

In the next decade, this community will focus on leveraging the rapidly developing technologies to provide extremely sensitive and precise measurements of the radiation from weak nuclear decay to search for new physics. Chief among these is the search for neutrinoless double beta decay and the direct determination of the neutrino mass. For ton-scale neutrinoless double beta decay searches, three fundamentally different technologies are currently employed,

Sidebar 10.1 Enabling Superconducting Technologies for Discoveries and Applications

Present and future nuclear science machines require specific R&D of enabling technologies, which push the state of the art significantly. Such demands have led, for example, to new developments in superconducting radio frequency (SRF) as well as in particle-source and target technologies based on superconducting magnets. All major nuclear physics facilities have established an R&D program in these areas and collaborative ties to industry partners. These efforts benefit not only nuclear science but also advanced accelerator facilities across the spectrum, including synchrotron light sources, free-electron lasers, neutron sources for materials research, and new technologies for radiation therapy and isotope production.

Two prime examples in SRF are the development for a future FRIB upgrade (FRIB400) and the ion-storage ring of the EIC. The FRIB energy upgrade to 400 MeV/u can be accomplished by adding additional cryomodules to the end of the FRIB linac. This possibility was incorporated into the design of the linac tunnel during construction, but requires new high-gradient cavities optimized for the energy range. Prototyping demonstrated the optimal design choice for FRIB400, which allows for a low heat load with high accelerating voltage (Figure 1). The development for FRIB400 has started with four superconducting cavities built by industry. The EIC storage rings will require a suite of superconducting cavities, including the most prominent group of so-called crab cavities, which will have unprecedented performance parameters. Compared to the High-Luminosity Large Hadron Collider's crab cavities, the development of the EIC crab cavity types is at the forefront of this technology.

Active research areas of the SRF community are high accelerating gradients and high quality (Q) factors. These areas are addressed by cavity processing, new superconducting materials and investigation of surface properties, the damping of higher order modes, and advanced cryomodule technologies. A new topic that needs attention is the deterioration of superconducting cavity performance owing to dust migration. New developments are mitigating this significant risk for the reliable operation of nuclear physics accelerators.

Polarized particle beams are essential tools for nuclear physics science experiments, and present R&D is addressing state-of-the-art polarized electron and ion beams. The polarized helium-3 source for the EIC could be facilitated by a new development spearheaded by a BNL–MIT collaboration and based on a high-field optical pumping technique using superconducting magnets. This technology will provide a source of polarized helium-3 for injection into RHIC/EIC using the existing Electron Beam Ionization Source (RHIC-EBIS) at BNL, which has been upgraded for EIC by the so-called Extended EBIS (Figure 2), and is based on an innovation motivated by the desire to produce copious amounts of polarized gas for lung imaging in the high field of an MRI magnet. Further, a polarized helium-3 target for CLAS12 using the same technology is under development by a JLab-MIT collaboration.

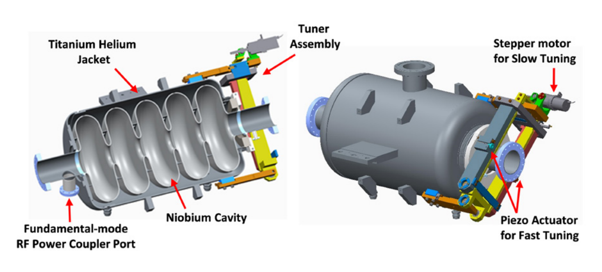


Figure 1. Proposed highly efficient FRIB five-cell, 644 MHz superconducting cavity for the FRIB400 upgrade [S78].

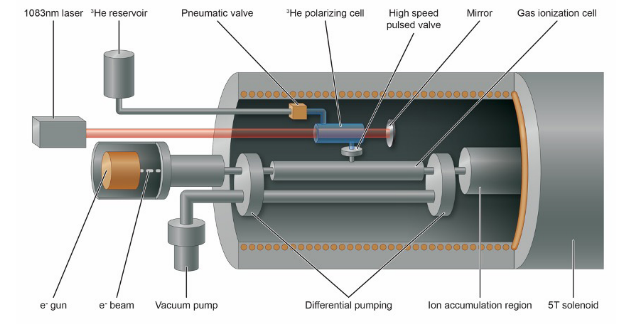


Figure 2. Schematic layout of the polarized helium-3 ion source under development at BNL. The pumping cell is located within the warm bore of the RHIC-EBIS 5 T solenoid. The polarized helium-3 atoms flow into the EBIS vacuum where they are ionized and confined in the intense 30 keV electron beam [S79].

all of which require extreme levels of material radiopurity and new methods for background rejection. These technologies are (1) CUPID, which leverages the extensive cryogenic and technical infrastructure built for CUORE, which operates “the coldest cubic meter in the universe;” (2) LEGEND, which utilizes high-purity p-type, ICPC germanium semiconductor detectors, enriched to more than 90% in germanium-76; and (3) nEXO, which employs a monolithic (5,000 kg) liquid xenon TPC, allowing the detectors to identify and measure background signals simultaneously. Determining the absolute neutrino mass requires well beyond sub-electronvolt accuracy, so new experimental paradigms are being developed. The Project 8 collaboration (Chapter 6) has been pursuing a new, frequency-based technique for measuring the energy spectrum of tritium beta decay. Superconducting sensor technology is at the forefront of emerging ideas in precision nuclear science and is a valuable training ground for a quantum-ready, nuclear-capable workforce. These new experimental methods have already enabled world-leading searches for BSM physics with nuclei.

The science carried out at the ATLAS, FRIB, and ARUNA facilities also drives detector innovations. For example, the FRIB Decay Station is a modular multidetector system that is uniquely positioned for discovery experiments at the extremes of the accessible regions attributable to the high sensitivity and relatively low beam-rate requirements of decay spectroscopy techniques. The Gamma-Ray Energy Tracking Array (GRETA) represents a major advance in the development of γ-ray detector systems. GRETA can provide order-of-magnitude gains in sensitivity and is critical to realizing the physics opportunities at FRIB and ATLAS, with fast-fragmentation, reaccelerated, and stable beams. The ARUNA laboratories have also driven innovation in several detectors, which among many includes the Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN), an active-target detector array developed specifically for experiments with radioactive ion beams. The ARUNA laboratories facilitate close collaboration between US universities and the DOE NP user facilities, facilitating innovation and training the low-energy nuclear physics workforce (Sidebar 9.2).

10.3 HIGH-PERFORMANCE COMPUTING

Computing is essential to all areas of nuclear science, from state-of-the-art theoretical calculations and realistic simulations of complex phenomena to high throughput data analyses and robust accelerator operations. High-performance computing (HPC) is now entering the exascale era: calculations can be performed at a speed in excess of 10^{18} operations per second (exaflops). Access to leadership-class supercomputers for the nuclear science community is provided through vital programs such as the Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program and the Advanced Scientific Computing Research Leadership Computing Challenge.

The evolution of exascale computing architectures is powered by new hardware technologies. Future advanced computing machines provide unprecedented opportunities to increase our understanding of nuclear science, but they also bring new challenges for their effective utilization. Investments in HPC computing hardware must be matched by the education of a skilled workforce able to take full advantage of the computational resources. This synergy requires strengthening collaborations between applied mathematicians, computer scientists, and nuclear physicists to design efficient algorithms and codes for new HPC architectures that employ computational accelerators such as GPUs. This effort has been supported by DOE’s SciDAC program, sparking major advances and innovations in lattice QCD (Chapter 3), nuclear structure and reactions (Chapter 4), nuclear astrophysics (Chapter 5), and fundamental symmetries (Chapter 6).

Although leadership-class machines push the boundaries of computational capabilities, not all problems and challenges require exascale computing. The nuclear science community has a large demand for “capacity computing” at computing centers across the nation, such as those part of the NSF Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS) program. Future nuclear science research programs will also require gathering, analyzing, transferring, and storing large amounts data at high speeds. In particular, nuclear physics experimental programs face new computational challenges owing to increasing detector complexity and experiments with higher interaction rates than previously seen. Simulations will be necessary to determine expected signals and backgrounds and to characterize hardware systems such as accelerators and detectors. Further computational needs will be driven by data acquisition, calibration, reconstruction, and analysis activities.

The large amounts of data produced by the nuclear physics community from experiments and theoretical calculations necessitate building high-capacity data centers and fast data connectivity. The DOE Energy Science Network connects researchers at more than 50 research sites and allows for more than 100 Gb of data transfer per second. The nuclear community should articulate best practices for data and code management within an emerging heterogeneous infrastructure of resources that connects facilities and academic institutions to decentralized storage architectures and federated and industrial computing clusters. Delivering developer productivity and performance portability in this web of computing resources will require composing nuclear workflows from existing workloads and data deployed across multiple organizations.

10.4 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

The ongoing revolution in the field of AI/ML has significantly influenced the nuclear physics community. For example, EIC could be one of the first large-scale collider-based programs in which AI/ML is integrated from the start. This development is hardly surprising because the nuclear physics community has been an early adopter of other innovative computer technologies and has frequently led their development. ML techniques are already standard in several branches of experimental and theoretical nuclear physics. Recent developments include the following:

- Automation and/or optimization of the operation of accelerators and detector systems, including development and validation of virtual diagnostics, improvement to beam sources and injector performance, data-driven system maintenance, automated learning for operator support, and anomaly detection and mitigation.
- Improved Monte Carlo calculations for lattice QCD and new approaches to solve the Monte Carlo sign-problem by ML-assisted contour deformation. These examples demonstrate AI/ML accelerating progress in nuclear theory.
- Systematic improvement of variational nuclear wave functions. The simple wave functions used in variational Monte Carlo, which are based on insight gained throughout many decades, are now being substituted with parametrizations using neural networks and their automatic optimization. These techniques have the promise to automate the process of discovery.
- Improved experimental design and real-time tuning, including improving experiments by intelligently combining disparate data sources such as accelerator parameters, experimental controls, and detector data. AI/ML enables intelligent decisions about data reduction and storage and can improve the physics content by using data compression, sophisticated triggers (both software- and hardware-based), continuous data quality control and calibration, task-based high-performance local computing, distributed bulk data processing at supercomputer centers, and online analytical processing.
- Improving simulation and analysis, including (1) improving sensitivity to allow more information to be extracted from datasets, decreasing uncertainty in results and increasing discovery potential; (2) decreasing simulation and analysis time to save costs and allow for a higher volume of scientific output by accelerating the feedback loop between experiment, analysis, and theory.

These developments highlight the significant amount of recent exploratory research and suggest a near-term increase by orders of magnitude in the use of AI/ML methods. Nuclear physics offers rich, complex data sets, ideally suited for AI/ML methods. It also provides rigorous, well-controlled contexts in which AI/ML successes and failures can be clearly distinguished. It is an ideal place to explore issues of interpretability and/or alignment that are much more difficult to approach in less contained datasets and pursued less vigorously by private enterprise.

The rapid growth in the field also poses some challenges to the field of nuclear physics. One of the lessons learned in the last decade is that AI/ML techniques become useful only at scale, when computational resources are substantial. Reaching this scale poses a challenge for individual researchers, especially those not connected to collaborations and/or experiments with significant computer resources. Furthermore, the application of AI/ML methods to different aspects of nuclear research is a high-payoff, low-yield enterprise. As such, we require a funding model that can provide timely resources, is not risk adverse, and embraces innovation. Mechanisms to foster communication between researchers within the nuclear physics and AI/ML communities should also be developed. Retention should be an important part of any AI/ML strategy for nuclear physics, because private-sector opportunities create a challenge to keep people with AI/ML expertise in nuclear physics.

10.5 QUANTUM INFORMATION, QUANTUM COMPUTING, AND QUANTUM SENSING

DOE, NSF, NIST, and other funding agencies are substantially investing in basic research for QIST and its applications. This investment has greatly benefited research at the interface of nuclear physics and QIST, has yielded important advances and benchmarking for future research, and is growing interdisciplinary collaborations.

With a substantial increase in computing capability enabled by superposition and entanglement, quantum computing and simulation (QCS) have the potential to provide unique capabilities for NP that far exceed those possible with classical computation alone (Sidebar 3.6). QCS is expected to uniquely provide predictive capabilities for several areas—elucidating the phases and phase transitions of strongly interacting matter governed by QCD, studying non-equilibrium phenomena such as evolution of matter created in heavy-ion collisions or after the Big Bang, elucidating energy-transfer mechanisms in supernovae explosions and neutron star mergers, constraining electroweak responses of nucleons and nuclei of relevance to nuclear astrophysics, searches for violation of fundamental symmetries of the Standard Model, and addressing low-energy nuclear reactions and fission processes—important for the study of nuclear matter at the limits of stability and for understanding the formation and role of nuclei in the universe. Furthermore, QIST tools are beginning to guide the design of more efficient classical nuclear physics simulations, and quantum entanglement is now being investigated as a new guiding principle in our understanding of nuclear physics phenomena and the Standard Model.

The pace and form of quantum hardware and algorithmic advances will determine when the community witnesses the ultimate quantitative impact of QCS. Laying the theoretical and algorithmic groundworks for quantum simulations, leveraging near-term quantum technologies while preparing for fault-tolerant quantum computers, and expediting the development of classical-quantum approaches that leverage HPC capabilities will be important aspects of integrating nuclear physics and QIST. The community will also benefit from strengthening its efforts in the co-design of quantum-simulation algorithms and devices for nuclear physics applications, better engaging with the DOE Quantum Testbed Program, and further developing reliable access to forefront quantum hardware, including industry platforms and other testbeds at national laboratories and universities. Programs and partnerships that enable collaborations across the field of nuclear physics in QIST will be increasingly valuable (Sidebar 10.2).

Advances made during the past two decades in atomic, molecular, optical, materials science, and cryogenic infrastructure are accelerating the development of quantum sensing (QSe) and quantum integrated systems. In some cases, these advances are providing revolutionary approaches to historically inaccessible problems. Several existing QSe technologies are already in use in certain high-priority nuclear physics programs, such as neutrinoless double beta decay, neutrino mass measurements, sterile-neutrino searches, precision tests of fundamental symmetries such as permanent electric dipole moment searches, and as probes of rare and exotic processes. Their targeted use in nuclear physics con-

Sidebar 10.2 Training a Quantum Workforce

The nuclear physics community's expertise in quantum matter and interactions benefits the development of a sustainable quantum workforce. A diverse and sustainable quantum-ready workforce is a necessity for both the nuclear physics and QIST communities. Owing to its broad application space, QIST attracts science talent into nuclear physics from a variety of backgrounds. This talent is then empowered by acquiring skills at the nexus of emerging quantum technology and computing trends in nuclear physics research. Recruiting and training this new generation of researchers will accelerate the development and integration of quantum technologies in nuclear physics research and propel growth and diversity in both nuclear physics and QIST.

Manqoba, who during his doctoral studies investigated noise-resilient quantum algorithms for computing nuclear states, will continue his career at the National Quantum Computation Center as a quantum applications engineer. Also pictured are Stefanie Guenther and Bjorn Sjogreen.

Figure 1. Western Michigan University graduate Manqoba Hlatshwayo (foreground) poses in front of LLNL Quantum Design and Integration Testbed (QuDIT) during a 2022 internship [S80].

tinues to grow, and expanding research and development in this area, including through investments in facilities at national laboratories and universities, is essential. Superconducting nanowire particle detectors are being explored for a broad range of unconventional applications from low-energy ion detectors to high-energy particle tracking. Significant sensing tasks in nuclear physics rely on arrays of sensors working collectively. Entangled states in such distributed systems improve sensitivities beyond classical limits and are a forefront research and development area within QSe.

Currently deployed QSe technologies involve instruments sensitive to low-energy transitions, such as superconducting tunnel junctions and transition-edge sensors (Quantum 1.0 sensors). Entanglement and/or coherence can be used as tools to reduce fluctuations below the standard quantum limit to build Quantum 2.0 sensors (e.g., using quantum squeezed states of light or entangled atoms). Leveraging Quantum 1.0 technologies to full advantage while participating in a coordinated, interagency development of Quantum 2.0 technologies and leveraging nuclear physics expertise to go beyond the current noise and scale limitations of solid-state devices is important for tackling nuclear physics grand challenges with the added capabilities of QSe. This advance will require mechanisms for facilitating access to mature Quantum 1.0 sensor technologies and democratizing the development of improved Quantum 2.0 sensors, dedicated R&D programs in QSe for nuclear physics, and partnerships with the DOE Isotope Program to maintain a stable and predictable supply of relevant rare isotopes.

The present vision for the potential benefits of QIST for nuclear physics and, conversely, the potential impact of the nuclear physics knowledge base on QIST, is summarized in Figure 10.1. Research at the intersection of nuclear physics and QIST will advance the development of QSe technology for NP; enhance the (co-)development, integration, and application of quantum-based simulation and computation hardware and techniques for nuclear physics; grow cross-cutting research and partnerships that leverage nuclear physics expertise to accelerate advances in QIST (including access to forefront hardware and fabrication); and expand the training of, and robust professional pathways for, a diverse and inclusive quantum-ready nuclear physics workforce, with cross-disciplinary collaborations in QIST. Furthermore, the establishment of a DOE NP Quantum Connection would enable a community-wide integration of QSe and simulation; facilitate sharing of resources and expertise among DOE NP, interagency programs, and the national and international QIST community; support bridge junior faculty and scientist positions, postdoctoral fellowships, and graduate and undergraduate students; and strengthen ties with the QIST community, technology companies, and other domain sciences.

In summary, the nuclear science community has identified the topics above as strategic opportunities (Chapter 1). The continuing adoption of these new technologies advances both scientific achievement and the growth of these and future technologies, which enable a new and exciting era of discovery.

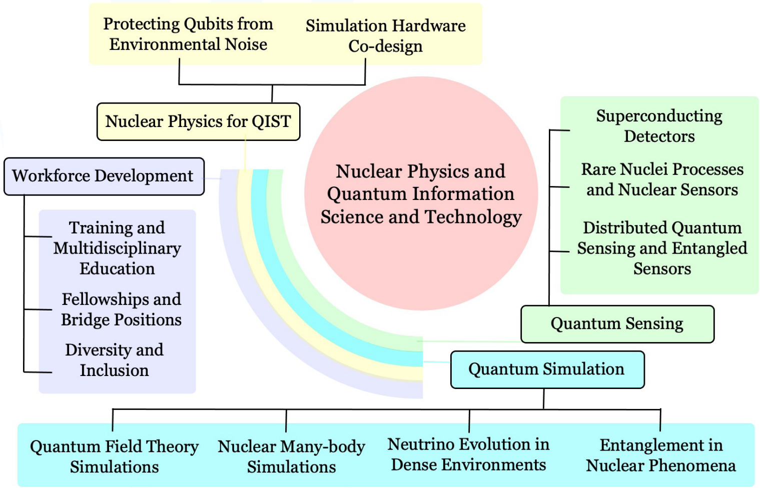


Figure 10.1. A schematic of the nuclear physics–QIST research and workforce ecosystem [46].

11 NUCLEAR SCIENCE APPLICATIONS

11.1 INTRODUCTION—WHY DO NUCLEAR SCIENCE?

The scientific discoveries and the products of pursuing new knowledge about atomic nuclei and the fundamental constituents of matter benefit humanity in myriad ways. Health care, national security, energy, industry, space travel, and the environment are just some of the areas in which nuclear science has shaped the modern world and continues to do so. Such research produces breakthroughs that can be applied to benefit people and protect the Earth. These breakthroughs are applied and basic science, not science fiction, yielding knowledge toward the production of carbon-free energy for a demanding world, treatment of human disease to reduce or eliminate suffering, space technologies to quench the human urge for exploration, and—closer to home—for national security and nonproliferation to ensure a safe future.

Since the field began at the turn of the 20th century, practical applications of nuclear science have been a motivating factor for continued scientific pursuits and the invention of new technologies. The quest for expanded knowledge of nuclear science in search of answers to some of the most fundamental questions, including what the universe is made of and why we exist, has led to innovations in particle accelerators, particle beam production, particle detection, medical isotope production, health care diagnostics, and techniques required for further discovery. Furthermore, the generation and dissemination of nuclear data are the lynchpin of ensuring safety and security for the nation and the world.

To harness all this information and make it available to science, data flow through the US Nuclear Data Program (USNDP). Many scientists and engineers are unaware of their dependence on nuclear data because it is “hidden” in models and computer simulation codes. However, recently DOE NP began hosting a series of annual Workshops for Applied Nuclear Data (WANDA) and created a Nuclear Data Interagency Working Group (NDIAWG) with members from across the federal government and private industry that identifies and addresses high priority nuclear data needs. Thus, this chapter begins with a discussion of nuclear data’s broad societal impact and its applications in the real world.

11.2 NUCLEAR DATA—THE FOUNDATION FOR APPLICATIONS, CAPABILITIES, AND COMPUTER SIMULATIONS

Accurate and accessible nuclear data are essential for supporting scientific research, national strategic goals, and an innovation-driven economy. For example, nuclear data libraries are infrastructure resources that support activities for advancing scientific exploration, technological developments, and applications that broadly benefit society such as new medicines, automated industrial controls, energy exploration, energy security, and isotope production. The USNDP is the domestic custodian of nuclear data. It is a critical component of the technical infrastructure central to accomplishing the missions of the federal government in the areas of nuclear nonproliferation, nuclear forensics, homeland security, national defense, space exploration, clean energy generation, and scientific research. As shown in Figure 11.1, more than 5,000,000 data retrievals from the National Nuclear Data Center (NNDC) have occurred each year since 2020. Figure 11.1 also indicates about a 70% increase in data retrievals from 2021 to 2022.

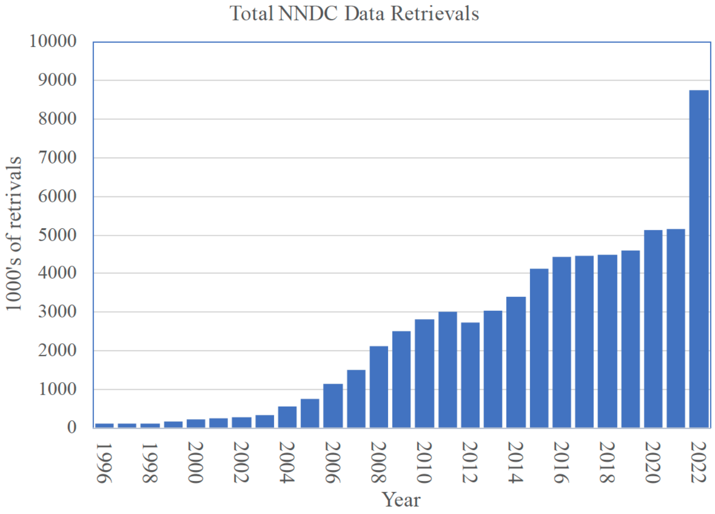


Figure 11.1. Total NNDC data retrievals per year from the USNDP databases at the NNDC from 1996 through 2022 [47].

Nuclear data generation, evaluation, dissemination, and use in computer codes and applications are part of an information flow dynamic with feedback loops as depicted in Figure 11.2. The types of nuclear data generated depend on the available research facilities and research capabilities. The amount of data produced of a particular type depends on several factors, including funding for facility operations, research priorities, and the data needs for applications. The measured and evaluated data are stored in data libraries that provide structured access for input to computer codes used in applications and nuclear models. Measuring new data yields improvements in and expanded use of computer codes as well as advancements in applications, which in turn stimulate refinements in nuclear databases and new measurements.

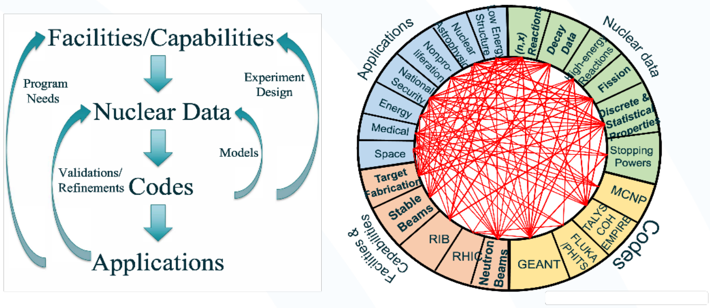


Figure 11.2. Nuclear data feedback loop and connections. *(left) Chart showing the information flow and dynamic feedback in the production, processing, and use of nuclear data. The flow starts with the production of data at nuclear physics research facilities. The next step involves data collection, evaluation and dissemination, followed by using the data to update the libraries of computer codes used in basic research and applications. The updates to the computer codes and applications in turn stimulate refinements to the nuclear data libraries and improved new measurements. (right) Chart showing the information-exchange connections between nuclear data, applications, facility capabilities, and computer codes [48].*

The mission of the USNDP and services offered by the NNDC evolve in association with national nuclear physics research and government priorities. Since

Sidebar 11.1 Fast, Accurate Nuclear Threat Detection

First responders need fast and accurate tools to determine whether an unknown source of radiation contains special nuclear material (SNM), such as uranium or plutonium, that can be used as fuel in nuclear devices. Scientists from LLNL, the Defense Threat Reduction Agency, Johns Hopkins Applied Physics Laboratory, and Radiation Monitoring Devices, Inc have developed the field-deployable Multiplicity Counter for Thermal and Fast Neutrons (MC-TF). Data from this instrument can aid in planning a response to an incident by providing information about the material's type, shape, and size.

Figure 1. Field-deployable Multiplicity Counter for Thermal and Fast Neutrons [S81].

MC-TF builds on the ability of SNM to sustain a fission chain reaction. This ability is unique relative to other materials that emit radiation. Because the neutrons from a fission chain are closely spaced in time and come in separated bursts, they can easily be distinguished from non-SNM sources, which emit neutrons continuously. Fission chains are thus separated by their temporal correlations. The timestamp of each such event is used to determine the total number of neutrons emitted in a fission chain. These data can then be used to extract features of the emitting source—its size, shape, and composition—and quantify the threat level.

An advantage of the MC-TF is that it can detect both fast (1–2 MeV) and thermal (<1 keV) neutrons, augmenting its use as a nuclear diagnostics tool. A previous iteration of the tool employed rare and difficult-to-obtain helium gas, which slowed the neutrons via multiple scattering before they could be detected. MC-TF uses two types of detectors: CLYC (cerium-doped cesium lithium yttrium chloride) detectors for thermal neutron detection and stilbene scintillators for fast neutron detection.

[S82]

MC-TF is also portable: the device is about the size of a small suitcase (Figure 1).

MC-TF uses an algorithm that can estimate the mass of the SNM and its multiplication factor based on only a few neutrons in only a few minutes. This efficiency is important when time is critical to determine the threat level. Such a device, deployed in the field, gives first responders an extra edge that could save lives.

the last Long Range Plan, NDIAWG was established to coordinate efforts to meet the nuclear data needs of federal agencies that support measurements and theory. The NDIAWG holds an annual conference, WANDA, that brings together program managers from various agencies and experts from the US nuclear science community. An important outcome of WANDA is that the DOE Office of Science, in collaboration with other agencies, set priorities for new nuclear data activities (e.g., new measurements, research instrumentation development, development of experimental techniques and codes, and theory work). The WANDA meetings, along with interagency collaboration, have broadened the scope of nuclear data activities in the United States and helped invigorate the community.

The bedrock of the USNDP is its evaluation and dissemination of nuclear structure, reaction, and mass data. Becoming an expert in nuclear structure evaluation is a demanding process that can take years of specialized training. The databases that contain these evaluations are managed by the NNDC at BNL. Partners in these USNDP evaluation efforts include Argonne, LBNL, ORNL, TAMU, TUNL, and FRIB. USNDP's vital work must be continued and expanded so that updates to the main nuclear structure data libraries are more frequent and comprehensive. The NNDC is updating the format of its data libraries to be more compatible with modern 21st century software and computer systems. The increased volume of new information and the need to make data more broadly accessible requires integrating artificial intelligence (AI) and machine learning (ML) tools into the compilation, evaluation, and dissemination of data. Finally, the activities associated with the nuclear data enterprise must be expanded to meet the requirements of data preservation and open data, designing and deploying a metadata architecture and management plan to curate, preserve, and disseminate low-energy nuclear physics data.

New data libraries and new theoretical modeling are important to support the broader nuclear data activities highlighted in the 2023 NSAC Nuclear Data reports. New infrastructure is needed to go beyond the low-energy nuclear reaction databases supported by the NNDC that primarily cover particle-induced reactions up to 20 MeV. The goal of returning to the moon and even reaching Mars requires reaction measurements and evaluations at much higher energies, up to 10 GeV/nucleon because high-energy galactic cosmic rays will impinge upon spacecrafts and the occupants, producing a cascade of secondary radiation, including charged particles, neutrons, and gamma rays. Experimentally validated databases of charged-particle and heavy-ion stopping powers are required for modeling these interactions with simulation codes.

None of these efforts will be possible without further workforce development. Recruitment and retention of new evaluators as well as the general nuclear data workforce to support these new programs are crucial. In particular, the USNDP will be strengthened by a more inclusive workforce.

11.3 NATIONAL SECURITY IN THE NUCLEAR AGE

The National Nuclear Security Administration (NNSA) is responsible for enhancing national security by applying nuclear science. Its primary mission is to maintain and enhance the safety, security, and effectiveness of the US nuclear stockpile, reduce global threat from weapons of mass destruction, respond to nuclear and radiological emergencies in the United States and abroad, and provide the US Navy with safe and effective nuclear propulsion. In carrying out its mission, the NNSA extensively leverages the nuclear physics research facilities and infrastructure amassed for basic research by DOE NP and NSF, the scientific and technical expertise within the nuclear science community, the education pipeline for basic research in nuclear science, and the nuclear data program. Nuclear theory is one of the scientific capabilities required by NNSA for advancing basic science and development of nuclear structure and reaction models used to calculate quantities where data do not exist or have large experimental uncertainties and to evaluate nuclear data.

The challenges of carrying out the NNSA mission demand a highly talented and diverse workforce educated in nuclear science and having specialized technical expertise. This workforce is developed and sustained by connections that are established and maintained with the US nuclear physics research community at universities and national laboratories. The NNSA Stewardship Science Academic Alliances was created to engage university groups in research relevant to its mission, stimulate collaboration between university and national laboratory scientists, and support opportunities for students to work at NNSA national laboratories. This program is one of the NNSA's central activities aimed at talent outreach and educating the next-generation NNSA workforce. The scientific expertise, substantial research infrastructure, and hands-on style of student research in experimental nuclear science at the ARUNA laboratories enable them to contribute significantly to the program's goals. For example, TAMU is an NNSA Center of Excellence in low-energy nuclear science. An illustration of the hands-on style of research in ARUNA laboratories is illustrated in Figure 11.3.

All components of the NNSA mission require broad expertise in nuclear science, access to a wide variety of accurate nuclear data, the capability to measure quantities when data do not exist or have large experimental uncertainties, and evaluating nuclear data. These capabilities are especially important for developing new techniques and technologies for applications in nuclear security. Examples of recent use of nuclear science in nuclear security applications are illustrated in Sidebars in this chapter on field-deployable nuclear threat detection (Sidebar 11.1), mapping radiation (Sidebar 11.2), and machine learning applied to nuclear security (Sidebar 11.3).

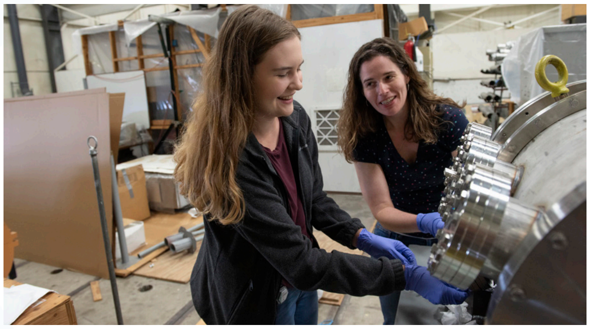


Figure 11.3. An undergraduate student working with a postdoc in the laboratory at the Cyclotron Institute at TAMU in 2019. *The postdoc is now an accelerator physicist, and the undergraduate is in graduate school in nuclear physics [49].*

Sidebar 11.2 Mapping Radiation and Making it Visible in 3D

The enormous advances in sensing and data processing technologies in combination with developments in nuclear radiation detection and imaging enable new ways to detect, map, and visualize nuclear radiation. The recently developed concept of 3D scene–data fusion (SFD) allows us to visualize nuclear radiation in 3D, in real time, and specific to radionuclides. It is based on multisensor instruments that can map a local scene and fuse the scene data with nuclear radiation data in 3D while the instrument is freely moving through the scene. This new concept is agnostic of the deployment platform and the specific radiation detection or imaging modality. For example, using gamma-ray and neutron-sensitive radiation detectors, they can be operated as omnidirectional gamma-ray and neutron imagers that can be remotely deployed on drones or on ground robots.

The 3D SDF concept has been demonstrated in numerous environments, including Fukushima in Japan (Figure 2), Chernobyl in Ukraine (Figure 1), and at the Savannah River Site in the United States to assess the radiological contamination and to enable more effective and safe decontamination and decommissioning efforts. SDFs provide new means to detect, map, and visualize radiological and nuclear materials relevant for the safe and secure operation of nuclear and radiological facilities or in response to accidental or intentional releases of radioactive materials for which a timely, accurate, and effective assessment is critical.

Figure 1. 3D reconstruction of a claw that was used to remove the radiologically contaminated debris from Reactor 4 of the Chernobyl Nuclear Power plant after the accident in April 1986. (left) A photograph shows the actual claw. (center) The photogrammetric reconstruction of the ~10 ft high claw with a simple radiation sign in front and some dumped truck tires in the back. (right) Visualization of the embedded cesium-137 contamination. This image was produced by projecting the gamma-ray image information onto the 3D photogrammetric surfaces. It illustrates that most of the cesium-137 contamination can now be found on the ground with dose levels of up to 0.4 mSv/h. The centimeter resolution reconstruction can be obtained within minutes [S83].

11.4 HEALTH CARE—NUCLEAR MEDICINE IS INDISPENSABLE FOR DIAGNOSIS AND TREATMENT

Radiology and nuclear medicine provide key methods in modern health care strategies for diagnosing and treating illnesses. Because of nuclear medicine's central role in the diagnosis and treatment of cancer, most modern medical centers have a nuclear medicine division either as a separate unit or as a part of radiology. Nuclear medicine is distinct from radiology in that radiology uses external radiation sources to image body structures and treat illness, whereas nuclear medicine techniques are based on detection of radiation from sources introduced into the body with the goal of imaging physiological functioning and treating illnesses (e.g., cancer and hyperthyroidism). Familiar examples of radiology modalities are 2D transmission images, 3D computed tomography (CT) imaging, and particle beam therapy for tumor treatment. Examples of nuclear medicine methods include positron emission tomography (PET) and labeled radiopharmaceuticals for imaging and treatment. Nuclear physics contributes to advances in nuclear medicine and radiology both directly and indirectly. The main indirect contribution comes from expanding the field of knowledge through basic nuclear physics research. Direct contributions include nuclear data, new measurements of nuclear

Using 3D SDFs in combination with advanced robotics systems tremendously reduces risk to workers performing tasks in high-radiation environments. For example, 3D SDFs can be mounted on drones or four-legged robots to map complex environments, which may be difficult or impossible to access for humans, to monitor the operation of nuclear power plants. Furthermore, SDF technology provides tools for more effective communication to the public during radiological incidents by overcoming the main concerns of not being able to see nuclear radiation.

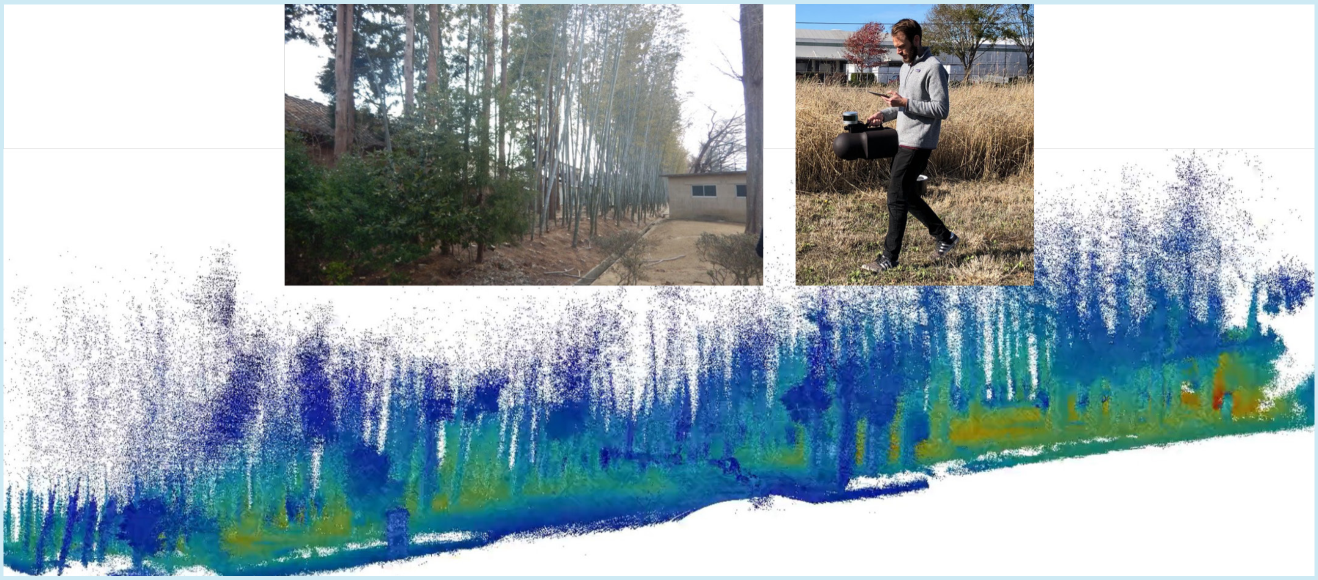


Figure 2. Bamboo forest in exclusion zone in Namie, Fukushima Prefecture, Japan. (top left) Photograph of forest with adjacent buildings. (top middle) Operator carrying the SDF-Portable Radiation Imaging Spectroscopy and Mapping system. (bottom) Measurement results created using an SDF-enabled instrument. A complete radiation field was reconstructed within this forest, specifically showing the distribution of cesium-137 in this environment. The complete 3D radiation map was obtained within 15 min while walking through this forest. The full digital reconstruction also allows inspection from different perspectives onto the scene and the ability to remove objects such as the buildings digitally to enhance the visibility of the contamination. These types of measurements can also be performed remotely on ground-based robots such as quadrupeds or on small unmanned aerial systems or drones [S84].

reaction rates, and structure properties of nuclei relevant to medical applications (e.g., isotope production and modeling nuclear reactions in tissue), and innovations in particle accelerators and detectors. The following examples describe recent advances in nuclear medicine and their connection to nuclear science research.

Theranostics is a recent development with substantial potential for increasing the effectiveness of cancer treatments compared with traditional approaches. It combines diagnostic and therapeutic applications using a radioisotope pair—one for diagnostics and the other for therapy—to label a specific pharmaceutical that has a high affinity for chemical structures associated with tumors. A theranostic radioactive isotope

Sidebar 11.3 Machine Learning in Nuclear Security, Nonproliferation, and Safeguards

Machine learning is a promising technology in several areas related to applied nuclear physics, such as homeland security, nuclear nonproliferation, and safeguards applications. One such area is the detection and identification of threat-source signatures in gamma-ray spectra in urban search, which requires the discrimination of often weak signals emitted by potentially dangerous radioactive materials from the large natural and anthropogenic backgrounds generally encountered in urban areas. Advances in the creation of highly realistic synthetic gamma-ray data of urban scenarios has allowed the generation of large datasets for training machine learning–based approaches without the need for long measurement campaigns. Unfortunately, a downside of machine learning is that understanding what aspects of the training sets the models have learned is often difficult. Tools have been developed and provided to the community to create "explanations" for gamma-ray spectrum models, such as highlighting the regions of a spectrum that the model used to conclude a certain isotope has been detected. These tools will elucidate how the models work, thereby guiding their further improvement.

Figure 1. Computer vision techniques, such as semantic segmentation, enhance the capabilities of radiation detection measurements. A facility is segmented into distinct material classes. The trajectory of the vehicle carrying the computer vision sensors and the detectors is overlaid in blue [S85].

Other efforts focus on machine learning methods developed in the field of computer visualization that process contextual data collected by sensors such as a camera or a lidar. The outputs from these algorithms can be fused with the radiation data to perform a variety of tasks. For example, images recorded using cameras installed on static sensor nodes placed throughout a city have been analyzed by neural networks that detect objects. The algorithm can extract characteristics, such as the color and make of a vehicle, that then can be shared and combined with nearby devices to increase the overall sensitivity of the sensor network for detecting unusual or illicit radioactive signatures. Semantic image segmentation is another technique used to enhance radiological searches. This method classifies each pixel in an image according to a predefined set of labels. The labels can be combined with the lidar data to create a 3D representation of an area (Figure 1). Each component in such a model can emit a different radioactive profile, better accounting for the background variability observed in free-moving systems.

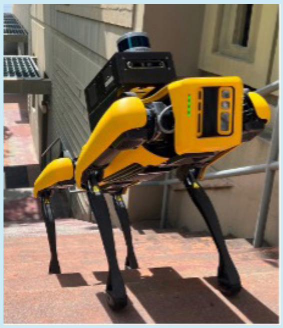


Figure 2. Boston Dynamics SPOT robot navigating stairs while carrying nuclear search equipment, including lidar and cameras [S86].

Automatically counting nuclear waste containers, enabling robots to investigate a nuclear storage facility autonomously (Figure 2), or supporting nuclear emergency response teams and remote experts are just a few more examples of research that is harnessing machine learning to advance nuclear safety in the United States.

pair can be used to identify the presence of a specific type of cancer and then deliver targeted radiation therapy to that cancer. Radioactive isotopes being developed for these treatments include gallium-68, which is a positron-emitting isotope that can be used for PET imaging to detect the presence of certain tumors. It is commonly used in conjunction with other theranostic isotopes, such as lutetium-177, for targeted radionuclide therapy. For example, recent research has demonstrated that gallium-68 and lutetium-177 attach to folate hydrolase I, also known as prostate-specific membrane antigen (PSMA), making it a highly effective diagnostic–therapy pair for prostate cancer. Gallium-68 decays by positron emission with a half-life of 1.13 h, enabling PET imaging of the regions in the body where the gallium-68 labeled pharmaceutical is concentrated; this concentration is proportional to concentration of PSMA in the tissue. Lutetium-177 beta-decays with a half-life of 6.72 days. Because of the low energy of the particles emitted in the decay, their kinetic energy is absorbed in the tissue in high concentration around the decay site (i.e., within a range less than about 2 mm), making it a highly effective therapeutic. The results of eight patients with prostate cancer who were treated with lutetium-177 radiotherapy after they had exhausted standard treatment options are shown in Figure 11.4. The treatment was administered for 3 months. The techniques used for these trials are described in M.S. Hofman et al., Oncology, 19, 825 (2018).

Beta therapy uses beta-emitting isotopes to treat different types of cancer. Beta particles typically have a longer range in tissue (on the order of 1–5 mm) than other charged particles and are the most frequently used emission particle for agents used in radiopharmaceutical therapy. Commonly used beta-emitting isotopes in targeted radiation therapy are iodine-131, yttrium-90, samarium-153, and lutetium-177. The most frequently used of these is iodine-131, which is used to treat thyroid cancer and for theranostic imaging to identify the presence of thyroid cancer. Yttrium-90 can be used for targeted radionuclide therapy of certain tumors, including liver cancer and neuroendocrine tumors.

Alpha (helium-4 nucleus) therapy involves delivering an alpha emitting nucleus to the cancer site. The low-energy alphas lose their kinetic energy in a very short distance in tissue, thus killing cancer cells and minimizing damage to the surrounding healthy tissue. Recent research has shown that targeted alpha therapy can effectively treat certain types of cancer, including prostate cancer. Some recent advances in alpha therapy include treatments involving actinium-225, an alpha-emitting isotope that has shown promising results in clinical trials for a variety of cancer treatments, including prostate cancer, breast cancer, and leukemia. Targeted alpha-particle therapy uses a specific tumor-targeting agent linked to an alpha-emitting isotope. This technique allows for more precise delivery of the radiation to cancer cells, reducing damage to healthy tissues. Combination therapy uses alpha therapy together with other therapies, such as chemotherapy or immunotherapy, to increase treatment efficacy. This approach is being studied in preclinical and clinical trials for a variety of cancers. New targeting strategies are being developed to improve the delivery of alpha therapy to cancer cells. For example, researchers are exploring the use of specific antibodies and nanocarriers to improve the specificity and efficacy of alpha therapy. Advances in imaging are being developed to improve the visualization and monitoring of alpha therapy. For example, researchers are using PET imaging to monitor the bio-distribution of alpha-emitting isotopes and to assess treatment response. Overall, these advances in alpha therapy are expanding the use of this promising treatment modality and improving patient outcomes.

Radiation Therapy used to treat cancer is a technological advance spurred by nuclear physics research. Radiation therapy for cancer treatment involves delivering a lethal radiation dose to the tumor while minimizing the radiation exposure of normal tissue. Light-ion beam therapy, such as proton therapy, is a precise form of radiation treatment for cancer. Because of the highly localized energy deposition of ions in tissue, light-ion beam therapy is a significantly better treatment method than conventional radiation therapy using x-rays or electrons. Another example in which nuclear science affects therapy is FLASH radiotherapy (RT), a technique involving the delivery of ultrahigh-dose-rate radiation to the target. FLASH-RT has been shown to reduce radiation-induced toxicity in healthy tissues without compromising the anticancer effects of treatment compared with conventional radiation therapy. Incorporating FLASH-RT into routine clinical radiotherapy for electrons, photons, and protons will require the continued development of accelerator and detector devices, likely leveraging nuclear physics techniques. A final example is boron neutron capture therapy (BNCT). BNCT is based on reactions that occur when boron-10 is irradiated with thermal neutrons, with subsequent alpha emission. BNCT has existed for decades but has recently re-emerged because of the new availability of compact accelerator-based neutron sources. These sources are derived from accelerator technologies developed for nuclear physics research. Combined with high-specificity third-generation boron carriers, these low-cost and small-footprint facilities have gained interest for use in hospitals.

Medical imaging systems provide powerful clinical tools for disease diagnostics and treatment. PET and single-photon imaging with a gamma camera, including the tomographic implementation in single-photon emission computed tomography (SPECT), are widely used and available clinically. Opportunities for imaging technology to overlap with nuclear physics detector technologies include the use of scintillating crystals, gas-based detectors, photodetectors, solid-state detectors, digital silicon photomultipliers and high-speed electronics for PET, SPECT, x-ray CT, and also proton/hadron particle therapy. Nuclear medicine camera developments rely on continuous innovation in radiation detectors, photodetectors, and electronics. Spatial resolution is an important parameter in medical imaging because it directly affects the ability to detect and localize small lesions and pathological changes in the body. Some recent advances in imaging resolution for nuclear medicine include the use of silicon photomultiplier (SiPM) detectors, which are highly sensitive photon detectors that have been shown to improve the spatial resolution of PET imaging. SiPM detectors can be used in digital PET scanners to improve image quality and reduce radiation dose to patients. TOF PET uses information about the time difference between the emission of two gamma photons to improve the spatial resolution of PET images. TOF PET can provide better lesion detection and localization, especially in larger patients.

SPECT is a nuclear medicine imaging modality that uses single gamma-emitting radio-pharmaceuticals to produce images. Recent advances in SPECT technology, such as the use of collimators with higher spatial resolution and improved reconstruction algorithms, have significantly improved image quality and resolution. Hybrid imaging, such as PET/CT and PET/MRI, combine the functional information of PET with the anatomical information of CT or MRI, giving a more complete diagnosis. New radiotracers are being developed to target specific biological processes with higher sensitivity and specificity, thereby improving lesion detection and localization. For example, radiotracers targeting PSMA for PET imaging of prostate cancer have shown improved detection of small lesions compared with conventional imaging methods.

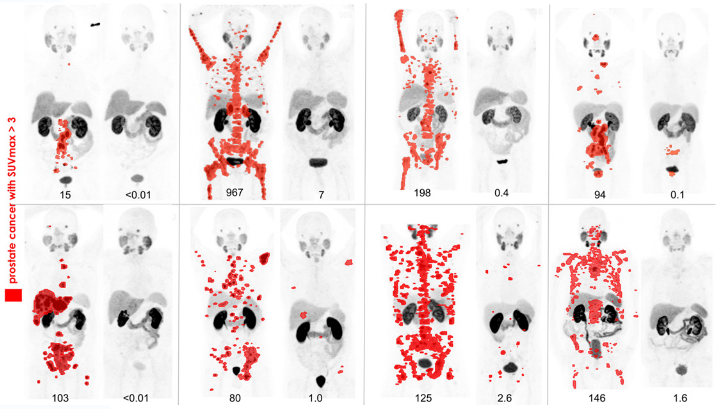


Figure 11.4. PET images using gallium-68 before (left side of each panel) and after (right side of each panel) radiopharmaceutical treatment with [lutetium-177]-PSMA-617 theranostic in eight patients with metastatic prostate cancer who exhausted standard treatment options. *The number at the bottom of each image is the PSMA level measured in the patients' blood before and after treatment. PSMA levels less than 4 ng/mL are generally considered normal, whereas levels greater than 4 ng/mL indicate risk of having prostate cancer. The treatment is a success in that the PSMA of all patients returned to normal levels [50].*

Medical isotope production, an application of nuclear physics techniques, is a $4–$6 billion global business. This business is projected to grow steadily at 1%–4% a year for the span of this Long Range Plan. In general, accelerator-based production of isotopes has advanced in recent years, particularly to produce longer-lived isotopes such as molybdenum-99 for medical use. Newer accelerator-based production methods have improved production yields and reduced waste. Targeted production methods, such as the use of neutron activation and proton bombardment, are being developed to produce specific isotopes that are in high demand for medical use, such as copper-64 and zirconium-89. Nuclear physics accelerator facilities contribute to isotope production and to the development of new techniques for producing medical isotopes. Examples include the production of astatine-211 at TAMU in collaboration with the MD Anderson Cancer Center and the medical isotope harvesting program being developed at FRIB. The metastable state of manganese-52m is in high demand for use in oncology, neurophysiology, and diabetes research. The upgraded FRIB400 could produce quantities of iron-52 as a manganese-52m generator to a level that could significantly improve regional supplies.

Advanced technologies being developed for next-generation accelerator facilities play an important role in improving both isotope production and beam therapy. For example, superconducting magnets are a key technology for particle accelerators, providing high magnetic fields and field gradients and thus compact accelerator solutions. Vital medical industry applications of superconducting magnets include MRI, compact cyclotrons, and hadron therapy systems. The MRI industry will advance with the development of high-field magnets: a feasible design using high-temperature superconducting wire allows for helium-free devices, thereby substantially reducing the operation costs and complexity of the magnet cooling system. New superconducting magnet technologies have enabled variable-energy, iron-free cyclotron designs with the required beam intensities; these magnets can even be mounted on gantries or tumor-irradiation systems.

11.5 THE IMPACT OF NUCLEAR SCIENCE ON THE ENVIRONMENT

Human activities associated with producing energy (Sidebar 11.4), manufacturing products, farming, and disposing of waste are the main sources of increased greenhouse gases in the atmosphere and contamination of soil and water. In the long term, these activities harm the planet and human health. Practices and policies to reduce the rate of pollution and contamination and to determine the effectiveness of decontamination efforts require regularly monitoring conditions via precision measurements of various data, including the carbon dioxide concentration in the atmosphere, air pollutants, contaminants in soil and fresh water, and changes in ocean currents. To this end, nuclear physics techniques contribute in important ways. Some examples are described in the following subsections.

11.5.1. The atmosphere and oceans

Nuclear physics techniques are used to study the Earth's complex climate systems using isotopic tracers, both radioactive and stable. For example, radioisotopes are used to study ocean currents. The global overturning ocean circulation plays an essential role in the climate system by accumulating and redistributing heat around the planet. Radiocarbon (carbon-14) and tritium (hydrogen-3) are used to determine sources, ages, and pathways of great ocean currents and water masses. Other approaches use fission products such as cesium-137 and strontium-90 to validate models of ocean currents. In some cases, because of these isotopes' low natural abundance, special measurement techniques are required. One such technique is accelerator mass spectrometry, a cutting-edge technology that is used to detect tiny amounts of stable or long-lived radioactive isotopes that are used in element tracing in climate and environment studies (e.g., mapping ocean and river currents, studying ocean and groundwater chemistry, and determining CO_2 and compound concentrations in the atmosphere over thousands of years).

11.5.2. Products and food

Modern lifestyles rely on the ready availability of a vast array of products and devices made from advanced and often complex materials that are expected to be dependable and efficient. At home, they include "soft goods," (e.g., plastics, textiles, detergents) often made from polymers, and "white goods," (e.g., sophisticated electronics) usually constructed using metallic alloys and composites. Mining, construction, industrial processing, and transport also rely on materials and advanced engineering that meet specified requirements. Industry and agriculture employ many analytical and monitoring methods to ensure the availability of products designed to improve our lives. Nuclear physics methods are used to increase the shelf lives of fruits and produce. Irradiation of agriculture products with gamma-rays from radioactive sources (e.g., cesium-137) kill bacteria and insect larvae while not harming the product, thereby increasing shelf life and reducing the risk of spreading pests. This process contributes significantly to the efficiency of delivering farm products from growers to consumers and has become one of the fastest-growing commercial methods to prevent the spread of regulated plant pests (e.g., fruit flies, mites, weevils) via trade in fresh commodities. Ensuring that produce is free from certain pests is a prerequisite for global trade in fresh produce. The detection of a single Mediterranean fruit fly in a produce container, for example, can lead to immediate import bans and devastating financial consequences for the exporting country.

11.5.3. Pollution

Proton and other ion beams at nuclear physics accelerator facilities are being used to employ proton-induced x-ray emission (PIXE), particle-induced gamma-ray emission (PIGE), and Rutherford backscattering to screen for toxic compounds and pollutants in water, soil, dust, and consumer products. These techniques are fast, have low detection limits, are nondestructive, or require little sample preparation. Recently, the need to identify products and drinking water supplies that contain polyfluoroalkyl substances (PFAS) has become urgent. PFAS are human-made fluorinated chemicals that have been linked to accumulated toxicity in humans and are a modern health crisis. These chemicals are a concern because many of them are environmentally persistent, and some have known ecological and human toxicities. Scientists at the ARUNA laboratories routinely use PIXE and PIGE to screen for contaminants. For example, PIGE tests of firefighters' gear revealed that significant quantities of fluorochemicals are being shed from the textiles used in the personal protective equipment during the in-service lifetime of the garment.

These measurements help to assess the magnitude of PFAS absorption through the skin and to recommend safety measures to reduce exposure for fire service personnel. In another environmental pollution project, researchers used PIXE to scan soil samples from the area of the George Washington Bridge on the Hudson River in Manhattan for heavy metals. Considerable amounts of lead were found in the soil at the base of the bridge, with decreasing concentration as the distance from the bridge increased. PIXE has been also used to quantify airborne pollutants, such as sulfur, in aerosol samples, helping to assess the effects of acid rain. These valuable data help identify the sources and elucidate the transport, transformation, and effects of airborne and soil pollutants.

11.6 ENERGY—NUCLEAR FISSION AND FUSION TOWARD A CARBON-FREE FUTURE

Continued US economic prosperity requires access to energy resources in sufficient quantities and at low enough cost to sustain an economic growth rate that is globally competitive. Since 2006, the top three en-

Sidebar 11.4 Nuclear Physics in Oil Well Logging

Nuclear physics principles are used in gamma-ray logging of oil wells, water wells, and mineral mines. **Gamma-ray logging** is a method of measuring naturally occurring gamma-ray radiation in rocks or sediment in a borehole or drill hole. Different types of rock emit different amounts and different spectra of natural gamma-ray radiation. For example, shales usually emit more gamma rays than other sedimentary rocks, such as sandstone, gypsum, salt, coal, dolomite, or limestone, because radioactive potassium is a common component in their clay content, and because they absorb uranium and thorium. This difference in radioactivity between shales and sandstones/carbonate rocks allows the gamma-ray tool to distinguish between shales and non-shales. Non-shales point to potentially hydrocarbon-rich areas. An advantage of the gamma-ray loggers over some other types (nonnuclear) of well loggers is that they work through the steel and cement walls of cased boreholes.

Using the most sophisticated, spectroscopic detectors with good energy resolution allows for **spectral logging** of gamma rays emitted from natural radioactivity in the rock formation. A spectroscopic logger can be used to map the fraction of elements (e.g., potassium [%], thorium [ppm], and uranium [ppm]) as a function of depth. Furthermore, spectral gamma-ray logs help identify specific clay types, such as kaolinite or illite, and are also useful for calculating the effective porosity of reservoir rock (Figure 1).

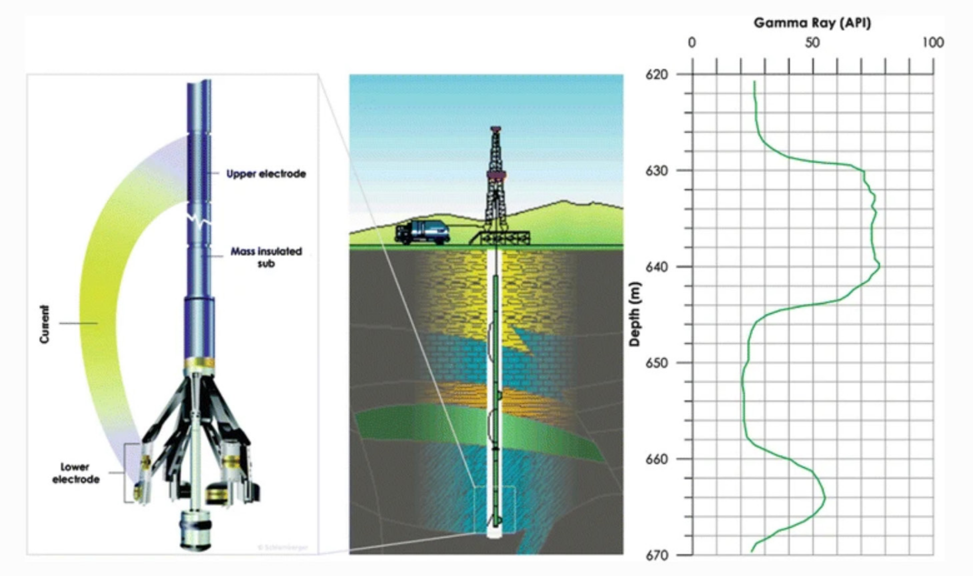


Figure 1. A logging tool (left), demonstration of a wireline logging operation (middle), and example of a recorded gamma ray log display (right).Density logging uses a source of gamma-ray radiation from a radioisotope, such as cesium-137, and gamma-ray detectors. The detectors are placed away from the source and measure the signal after attenuation by the rocks. Neutrons are also used in oil logging: they have different interaction mechanisms than gamma rays and can provide different information about the formation. Several types of radioisotopic sources generate the neutrons, and detectors measure the resulting neutron and gamma-ray signals, which are used to compute various properties of the formation such as the porosity [S87].

ergy consumers have been China, the United States, and Russia. The accumulated damage to the planet caused by burning fossil fuels for massive energy production is now clear. Industrialized nations are leading the global campaign to reduce carbon emissions while maintaining economic growth. Their early efforts are based on technological innovations, including energy efficient smart appliances, improved building and window insulation by engineering and developing new materials, electrification of vehicles, and investments in renewable energy sources such as wind, solar, and hydroelectric. For electrical energy generation, many nations are replacing coal with natural gas, which is a much cleaner fossil fuel in terms of heat production per ton of emitted carbon. In the United States, 38% of the current annual energy production is used for electricity, and 28% is used for transportation. As the nation transitions toward electric vehicles, a larger share of energy production will be electricity generation. These efforts are a good start and move human activities toward reducing carbon emissions. However, these actions only partly address the issues associat-

Neutron-induced gamma-ray radiation measurements (spectroscopy) directly identify chemical elements, allowing precise determination of hydrocarbon content. These advanced systems use active neutron sources and several gamma-ray spectroscopy detectors, both designed by nuclear physicists. The physicists conduct advanced modeling studies and produce algorithms to compute properties of the rock formation, the quantity of hydrocarbons, and how easily they can be extracted.

Current developments of oil well and mineral mine logging systems aim to advance efficiency and precision of spectral gamma-ray identification (Figure 2), including efforts to validate Monte-Carlo simulations using standard nuclear physics software packages such as Geant4. This improved capability translates into measurement speed and accuracy. Higher flux neutron sources and high-efficiency radiation detectors are being developed.

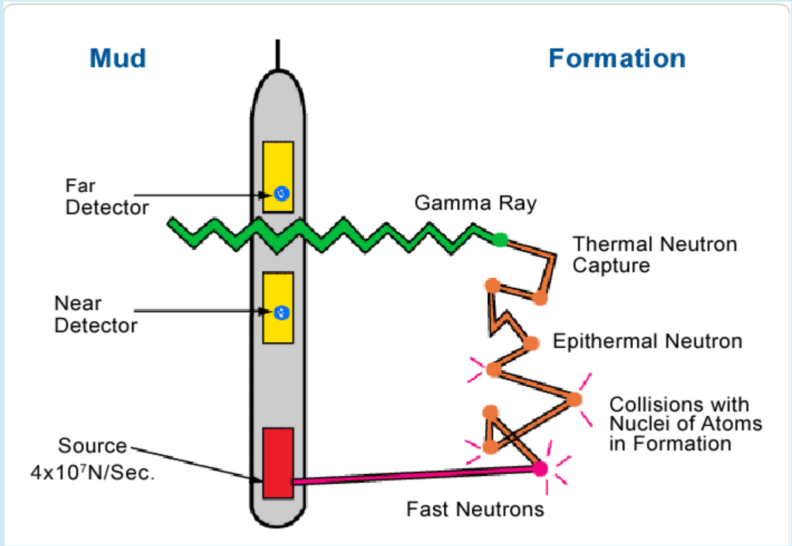


Figure 2. A generalized representation of a neutron logging tool for oil well logging [S88].

ed with long-term sustainability (i.e., beyond a human life span). The solution for long-term carbon-free electrical energy production has historically come (and still comes) from nuclear science: fission for the intermediate timescale and fusion for the long term (e.g., beyond the 21st century). The US nuclear science community is contributing to the development of the next-generation nuclear fission reactor and is advancing the science relevant to developing fusion reactors.

A workforce with broad expertise in low-energy nuclear science is essential for developing the next-generation nuclear fission reactors and finding solutions for long-term management of spent nuclear fuel. In addition to the normal wear of materials and systems in a thermal electric power plant, the materials in the reactor core of a nuclear power plant are exposed to high levels of radiation that cause damage at the subatomic level. Monte Carlo simulation codes model nuclear reactions inside the reactor core and walls and the transport of neutrons and charged particles in the fuel assembly and reactor walls. The simulations' accuracy depends directly on the precision of the reaction cross section, nuclear mass, and nuclear decay data used in the codes. The techniques used in basic nuclear physics research to simulate experiments are adapted for modeling reactors and radioactive materials in long-term storage. Furthermore, research aimed at better understanding and modeling the neutrino energy spectrum from reactors contributes to the basic science of technologies for remotely assessing the radioactive content of a reactor core during operation. Such technologies would be used to monitor reactor operation for compliance with nonproliferation agreements. New highly accurate cumulative fission-yield measurements are being made using gamma-ray counting techniques that can measure fission products with half-lives down to seconds. These data are important input in simulating spent nuclear fuel burnup.

Nuclear fusion awaits technologies that will enable its implementation on an industrial scale. In December 2022, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory achieved energy break-even (also referred to as ignition) for the first time. Ignition was also achieved in a subsequent shot in July 2023. Nuclear physicists have been crucial in developing and fielding diagnostics at NIF that are used to measure key properties of the implosion. As discussed at a recent fusion energy meeting at the White House, nuclear physics is key for further advances in fusion energy because it provides high fidelity models of neutron transport and the cross sections needed for tritium breeding. Growing interest exists in using the high neutron flux produced in fusion at NIF for basic nuclear science and in studying matter at high energy density. Additionally, nuclear physicists are applying their expertise in polarized nuclear targets used in basic research to explore the possibility of enhancing fusion's energy yield by using polarized deuterium and tritium or helium-3 fuel (Sidebar 11.5).

11.7 MATERIALS TO IMPROVE PARTICLE DETECTION

Nuclear physics research engages in the development and commercialization of new materials to improve the performance of subatomic particle detectors. Such detectors are employed in DOE and international accelerators performing ground-breaking research to expand our understanding of the subatomic world. These materials also have applications in homeland security.

For example, high performance scintillator materials are needed for particle identification and measurements of energy and momentum of particles in modern nuclear physics experiments. Achieving high-quality science at nuclear physics facilities requires the measurement of particle energy with excellent calorimeter detector energy resolution. Crystals such as lead tungstate have been used in precision calorimeters, but their production is slow and expensive. A collaboration of small businesses and universities supported by the DOE Small Business Innovation Research program has been addressing this need for alternative high-performance scintillator materials by developing the basis to replace such crystals with scintillating glass that is simpler and faster to produce in large quantities while meeting the desired specifications. The ability to manufacture novel high-performance glass scintillators will prove useful not only for calorimeter detectors but also for homeland security applications in which such scintillators should significantly reduce the false-alarm rate in passive nuclear detection systems and allow for a wide range of deployment scenarios. Fast response time and radiation-hard glass ceramics will find use in the scintillator market for security applications as active material for radiation portal monitors at locations such as ports where cargo screening with large throughput is required.

11.8 ELECTRONICS—RADIATION EFFECTS ARE KEY TO MINIATURIZATION

Miniaturization of integrated circuits is revolutionizing the electronics industry. Microelectronics are ubiquitous; they are the enabling technology in most modern electronic devices used in business, communications, appliances, system controls, medicine, aviation, space travel, vehicles, energy, national security, and research. As the basic circuit components (transistors, resistors, and capacitors) are made smaller, new challenges arise with each reduction in size. Single-event upset (SEU) is an important effect that must be overcome in each new generation of electronic chips. An SEU, also referred to as a single-event error (SEE), is a change of the state of a circuit caused by one ionizing particle. The state change is due to the free electric charge created by ionization in or near a logic element (e.g., a memory bit). SEUs cause transient logic errors but do not permanently damage the circuits. To mitigate the SEU effects, chip manufacturers conduct extensive SEU analysis of their chips by exposing them to different types of radiation. The evaluation of radiation effects has been required for the space and aviation industries for several decades, and because of the rapid push toward smaller circuit components, it is becoming important for applications in the automotive and medical device industries and in manufacturing.

Nuclear physics facilities provide a variety of particle beams for this important aspect of chip development. In the United States, electronics SEU testing is conducted at nuclear physics accelerator facilities using charged-particle and neutron beams at TAMU, LBNL, FRIB, LANL, and TUNL (Sidebar 9.3). Testing is also conducted with low-energy neutrons at research reactors.

Radiation hardening is the most used process for enhancing the resistance of electronic circuits to damage or malfunction caused by high levels of ionizing radiation. Hardened chips are often made on insulating substrates instead of the usual semiconductor wafers. A space-grade chip on insulating substrates must survive doses many orders of magnitude higher than a normal commercial-grade chip. Before they are sent into space, radiation-hardened products are usually evaluated using a low-energy gamma-ray source or high-energy particles generated at low- and mid-energy accelerator facilities.

Sidebar 11.5 Enhancing Fusion Reaction Rate With Spin-Polarized Fuel

Expertise in fundamental nuclear science research is now contributing to the pursuit of zero-carbon-emission energy production. A collaboration among the DIII-D National Fusion Facility, ORNL, and nuclear science principal investigators from Jefferson Lab and the University of Virginia is preparing for the first in situ demonstration experiment of spin-polarized fusion. This experiment would harness the reaction d + 3He → α + p, the nuclear-isospin mirror reaction of the standard d + t fusion reaction. Research at the University of Virginia using a clinical MRI scanner has already demonstrated that 2 mm diameter glow-discharge polymer (GDP) fusion fuel shells can be filled with polarized helium-3 gas (Figure 1). The fuel shells retain their polarization for about 3 days at 77 K, allowing ample time to be loaded into a cryogenic gun for tokamak injection.

The initial goal of this multi-institution project is the first in situ measurement of the fuel–polarization lifetime in a high-temperature plasma. Nuclear scientists are essential collaborators in this endeavor, providing the critical expertise in polarizing fuel pellets and polarization monitoring.

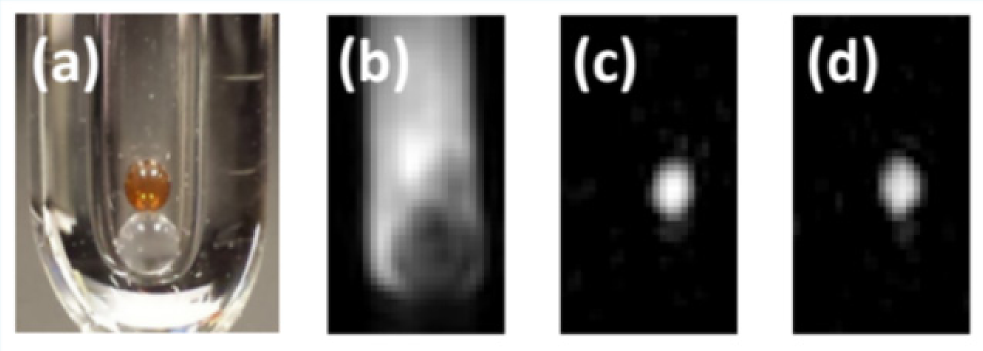


Figure 1. (a) A GDP fuel pellet is placed inside a glass tube and on top of a glass bead. (b) An MRI scan just after the tube was flooded with polarized gas. White regions indicate polarized helium-3, which then permeated the fuel shell for about 10 min. The tube was then cooled to 77 K, sealing the GDP wall. (c) MRI image taken 15 min later, after the helium-3 outside the shell was pumped away. (d) MRI scan 6 h later, showing nearly no indication of decline of the helium-3 polarization inside [S89].

12 BUDGET

Thanks to investments made by DOE and NSF, we are at the threshold of a new golden age of experimental and theoretical nuclear physics discoveries with the means to study a wide range of rare nuclei, gain rapidly evolving insights into neutron stars, execute new precision measurements using nuclei to search for physics beyond the Standard Model, and begin foundational efforts to map the nucleon in 3D and understand the glue that binds us all together. This funding has enabled construction of world-leading accelerator facilities while supporting research in QCD physics, nuclear reactions, nuclear structure, astrophysics, fundamental symmetries, and neutrino physics as well as development of a technically talented innovative workforce (Sidebar 12.1). We stand prepared to address the nation's needs, from developing cutting edge technologies in accelerators, detectors, quantum sensors, and HPC, to enabling advances in nuclear medicine and assuring the radiation resilience of our assets in space and developing innovators for the future through our unique multifaceted educational experiences. This section describes the needed resources to meet these goals while being responsible stewards of taxpayer dollars.

12.1 2015–2022 BUDGET OVERVIEW

Federal funding for nuclear physics research is provided by the DOE NP and by the NSF Nuclear Physics program within the Physics Division of the Directorate for Mathematical and Physical Sciences (MPS) and is guided by the Long Range Plans for nuclear science that the community has produced since 1979. The recommendations of the 2015 Long Range Plan were as follows:

- Capitalize on investments made, including utilization of the completed CEBAF 12 GeV upgrade and the upgraded RHIC facilities, completing FRIB construction, and sustaining the targeted program of research in fundamental symmetries and neutrinos.
- Develop and deploy a ton-scale neutrinoless double beta decay experiment.
- Construct the EIC following the completion of FRIB.
- Invest in small-scale and mid-scale projects.

The 2015 Long Range Plan projected that these recommendations could be attained within a modest-growth funding scenario, defined as 1.6% real growth per year above constant effort.

Several significant milestones were achieved during FYs 2015–2022. Construction of the 12 GeV CEBAF upgrade was completed in FY 2017, and FRIB construction was completed in FY 2021—ahead of schedule and on budget (Sidebar 12.2). The EIC attained CD-1 in June 2021. Progress was made toward developing a ton-scale neutrinoless double beta decay experiment, which attained CD-0 in 2018, although deployment was delayed because minimal funding was available for new projects. In order to construct and optimally operate our large facilities, which are investments in the long-term future of the field, the level of support in other areas of the DOE nuclear physics budget stayed constant or decreased.

Figure 12.1 shows the DOE NP funding in FY22 dollars separately for Research, Facility Operations, Isotope Program, Construction, and the one-time funds allocated in FY 2022 through the Inflation Reduction Act (IRA). Also shown is a small investment in projects. Because DOE Isotope R&D and Production (DOE IP) was moved out of DOE NP and established as a separate program within DOE SC in FY2022, the discussion that follows concerns the DOE NP budget without the isotope program to allow for comparing like funding across years. The funding involved in these DOE NP base budgets, without the FY 2022 IRA funds, followed the modest-growth scenario through 2018, but then lagged and fell slightly below constant effort. This scenario, coupled with the priority placed on optimal operations of the national user facilities—at least toward the end of the period under discussion—resulted in highly limited funding for research and projects. The baseline funding grew slightly from FY 2021 to FY 2022, but, in real terms, remained at essentially the FY 2015 level once DOE IP is removed from consideration.

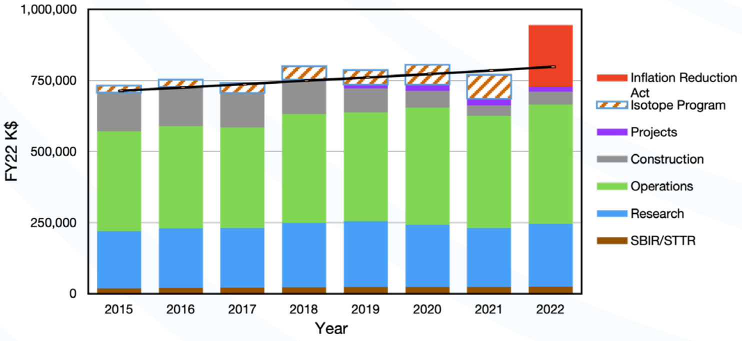


Figure 12.1. The distribution of DOE NP funding for different types of activities from FY 2015 to 2022 (historical data) in FY22 $K. *DOE IP was moved out of DOE NP and established as a separate program within the DOE SC in FY 2022. The black line represents the 2015 Long Range Plan modest-growth scenario, with 1.6% annual real growth for the base program with DOE IP excluded.*

In the 2015 Long Range Plan, the modest growth scenario anticipated that as funds needed for FRIB construction decreased, funds would be allocated to EIC initiation and to projects, including neutrinoless double beta decay experiments. As shown in Figure 12.2, the sum of funds for construction and projects decreased from 2018 through 2021, but still allowed limited investment in the EIC and modest growth in funds for projects..

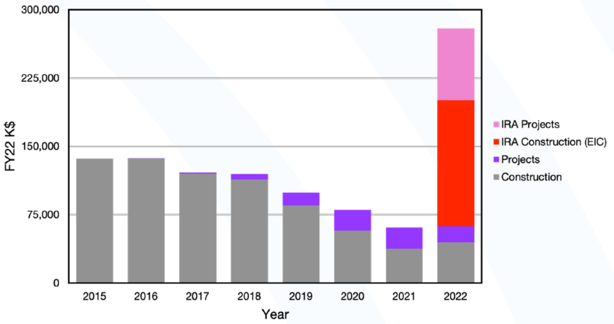


Figure 12.2. DOE funds for construction and projects, FY 2015–2022 in FY22 $K (historical data).

In FY 2022, the influx of $217 million from the IRA had a significant positive effect, providing funds for several projects that had been postponed under the constant-effort base funding, including GRETA, MOLLER, and HRS. These funds also allowed the EIC construction planning to proceed. The IRA funds provided $8 million to support planning for the three neutrinoless double beta decay experiments: CUPID, LEGEND-1000, and nEXO. The IRA funds thus advanced these major experimental efforts that had been envisioned in the last Long Range Plan. However, larger systemic issues, including the underfunding of the research budgets that support people, within the DOE NP budget were not ameliorated by the IRA funds. Another trend visible in Figure 12.1 is the growth of the facility operations budget, which increased from around 50% of the DOE NP base budget in FY 2015 to nearly 60% in FY 2022. Within the essentially constant-effort budget profile described above, the increased operations constrained funds available for the rest of the nuclear physics program, including research and construction/projects.

Total NSF funding for nuclear physics is shown in Figure 12.3 in FY22 thousands of dollars. One of the most significant changes during the period of FY 2015–2022 was the closure of the National Superconducting Cyclotron Laboratory (NSCL). The transition from the NSF-supported NSCL to the DOE-supported FRIB facility was carefully coordinated between Michigan State University, NSF, and DOE and was a model of interagency cooperation. The NSCL funding had included support for both operations and research. The cessation of NSF funding for NSCL was partially compensated by increased funding for research grants through the Nuclear Physics program within MPS, and researchers previously supported directly by NSCL funds transitioned to competitive NSF grant funding. During FY 2015–2022, the nuclear physics community successfully obtained Major Research Instrumentation Program and mid-scale NSF funds. These funds are competed either agency-wide or across MPS.

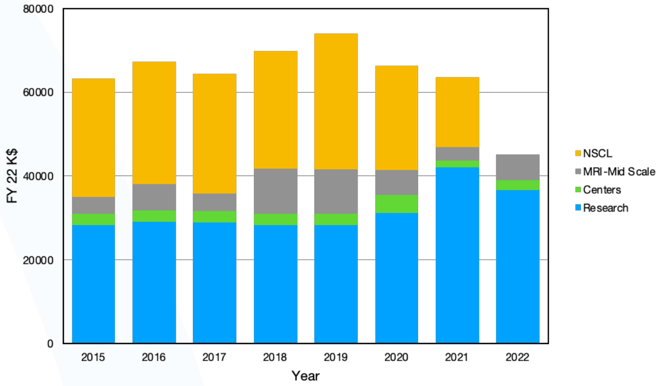


Figure 12.3. Distribution of NSF Nuclear Physics program funding for different types of activities from FY 2015 to 2022 in FY22 $K (historical data).NSCL funding ended at the end of 2021.

12.2 2024–2033 BUDGET PLANNING

The charge to NSAC requested a description of the potential impacts and priorities under two budget scenarios: constant effort and 2% modest growth using the FY 2022 enacted level as a reference. Since the charge was delivered to NSAC, the FY 2023 budget was enacted, and the CHIPS and Science Act was passed. The following discussion addresses what can be accomplished under each of the following scenarios—the CHIPS authorization, modest growth based on FY23 dollars, modest growth based on FY22 dollars, and constant effort—to position the United States nuclear physics community to capture new scientific discoveries and advance new technologies for the nation.

This Long Range Plan recommends the following:

- Capitalize on the extraordinary opportunities for scientific discovery made possible by recent investments.
- Lead an international consortium that will undertake a neutrinoless double beta decay campaign, building ton-scale experiments.
- Complete the EIC.
- Capitalize on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Many exciting opportunities for discovery science and benefits for the nation could be realized with the funds authorized in the CHIPS and Science Act. In particular, funding for DOE NP at the levels authorized by the CHIPS and Science Act (Figure 12.4) will enable the nuclear physics community to continue its world leadership in nuclear science and deliver innovations and innovators for the nation.

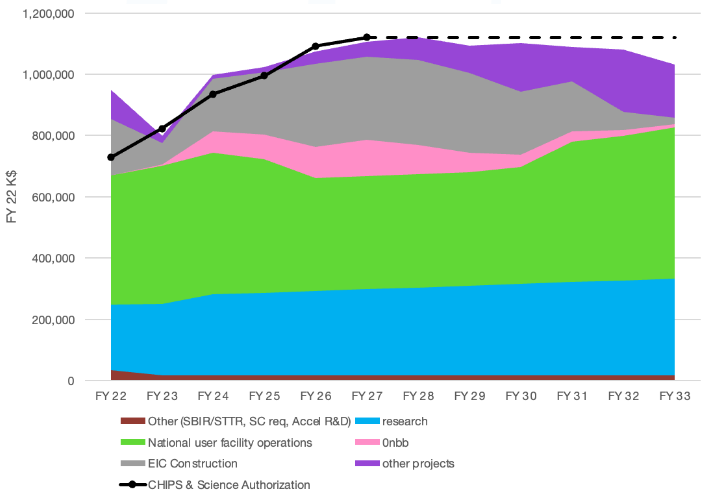


Figure 12.4. Funding as authorized by the CHIPS and Science Act will enable a robust program of discovery science and benefits for society. *This funding profile includes the required DOE contributions (e.g., to SBIR/STTR, Accelerator R&D) (brown), funding for a research program at the level of 35% of the enacted FY22 budget (without IRA funds), increasing annually by 2% over inflation (blue), funding for optimal operations of national user facilities (green), funding for the US portion of an international campaign of three ton-scale neutrinoless double beta decay experiments (pink), funding for EIC construction on a technically driven timescale (gray), and funding for other projects (purple). All numbers are in FY22 $K. The black line is the level of funding that was authorized by the CHIPS and Science Act, and the dashed extension represents constant effort after FY 2027.*

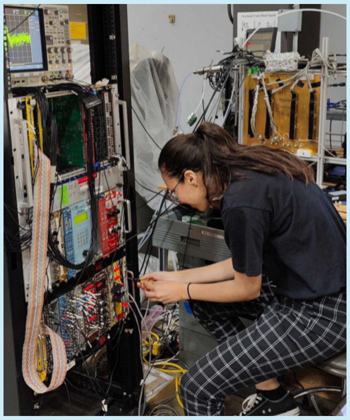
This CHIPS and Science profile increases the base research budget by 2% over inflation annually and provides an initial increase of 13% in FY 2024. This amount will enable a long-deferred investment in the people who drive the nuclear physics enterprise, most notably the graduate researchers, many of whom are struggling to live on their current stipends. University-based groups will be able to educate more innovators of tomorrow and grow the STEM pipeline. As is

Sidebar 12.1 Developing Intellectual Infrastructure for Science and Society

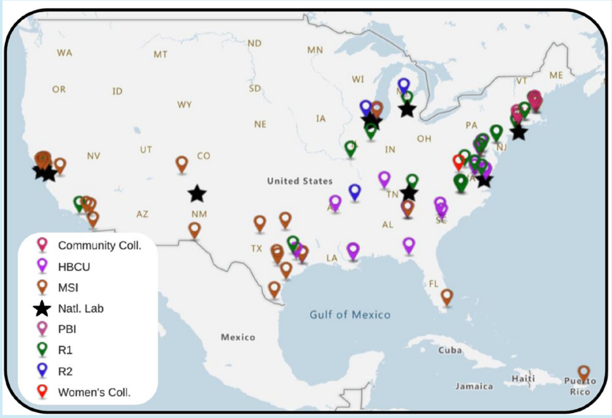
In 2021 Nuclear Physics issued a Funding Opportunity Announcement to enhance opportunities for underserved communities by connecting students from minority-serving institutions to DOE NP–funded programs. Funded grants supported 200 students at 91 institutions (see map). This successful DOE NP effort laid the groundwork for the DOE RENEW program.

One such grant was Texas Research Enhancing Nuclear Diversity (TREND). Daniela Ramirez Chavez (left) and Diana Carrasco-Rojas (right) were both students from University of Texas at El Paso (UTEP) who spent the summer of 2022 at Texas A&M University (TAMU) as part of this program. They both continued their research remotely during the academic year. After graduating, Daniela spent 9 months as a research associate at TAMU before beginning her doctorate in nuclear physics at MSU in fall 2023. Diana is continuing her education in a medical physics doctorate program at the University of Texas MD Anderson Cancer Center.

Diana Carrasco-Rojas solders a CosmicWatch detector for use at UTEP [S90].



Daniela Ramirez Chavez sets up electronics during a research assistantship at TAMU [S91].



[S92]

Sidebar 12.2 Delivering World-Unique Accelerator Facilities

The nuclear science community has a history of reliably delivering large, world-unique, accelerator-based user facilities safely, on time, and within budget by following the NSAC Long-Range Plans: ATLAS at Argonne, CEBAF at Jefferson Lab, and RHIC at BNL. Noteworthy since the last LRP, the CEBAF 12 GeV upgrade was completed on time and on budget in 2017 (Figure 1), and in 2022, the $730 million FRIB at Michigan State University was completed on budget and ahead of schedule after a 13 year construction project (Figure 2). One week after the ribbon cutting, the first experiment was completed. The science results of that experiment were published in November 2022 (“Crossing N=28 Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB” H. L. Crawford et al., Phys. Rev. Lett. 129, 212501).

Figure 1. (left) The FRIB heavy-ion accelerator uses a continuous-wave superconducting heavy-ion driver linac capable of producing 400 kW beams of all elements from uranium. (right) In November 2022, a multi-institutional team of scientific users published the results of the first scientific experiment at FRIB in Physical Review Letters. To perform the study, the rare isotopes were implanted into the center of the FRIB Decay Station Initiator (pictured) [S93-94].

Figure 2: The CEBAF facility at Jefferson Lab is a world-leading electron accelerator for exploring the nature of matter in depth, providing unprecedented insight into the details of the particles and forces that build our visible universe. (left) An aerial view of JLab. (right) Components of the CLAS12 detector system are assembled and installed in CEBAF’s Experimental Hall B [S95-97].

detailed throughout this Long Range Plan, many of these students contribute to the nation's prosperity through careers in national security, healthcare, technology, and education. Small-scale projects that provide hands-on experiences to young scientists would be funded. The much-anticipated FRIB has just commenced operations; optimal operations would allow the nation to reap the scientific rewards of that investment. Optimally operating RHIC for this final phase, before it is shut down for EIC construction, would allow the completion of an exciting physics program with the data from sPHENIX. The MOLLER experiment, currently being constructed, would benefit significantly from the Jefferson Lab's optimal operations. Funding would be available to mount a comprehensive neutrinoless double beta decay program with our international colleagues on an expeditious timescale. Additional projects would keep our community innovating and leveraging these facilities. The EIC would be able to launch into construction as soon as RHIC completes its science mission. To realize the EIC, we are ceasing operations of one of our flagship facilities (RHIC) in the coming years to redirect the operations funding toward EIC construction to maximally leverage previous investments and set a path toward the future. With the understanding that federal budgets are dynamic and influenced by sometimes shifting political needs, it is important to note that even if the exact funding profile cannot be achieved each year, funding increases consistent with the CHIPS and Science profile will be utilized efficiently to bring timely benefits for the nation.

In the event that the full funding authorized by the CHIPS and Science Act is not realized, and funding for nuclear physics is consistent with modest growth (2% annual real growth above inflation), the nuclear physics community can still deliver a compelling program of discovery science that will also convey significant societal benefits. However, difficult choices will be necessary, based on the Long Range Plan recommendations. The EIC can still be realized but will be delayed relative to the technically driven funding schedule depicted in Figure 12.4. A modest investment in the research community, by raising the fraction of the budget invested in research to 32%, can address the most pressing issues. For example, one-third of this increase in the research budget, if dedicated to increasing graduate researcher pay so that it is commensurate with their local cost of living, will attract the brightest minds to this exciting science and a future STEM career. The modest-growth scenario also allows neutrinoless double beta decay experiments to be actualized on a delayed timescale and enables the national user facilities to run their programs, albeit with a reduction in operations below optimal levels. Because the most recent enacted budget is FY 2023, corresponding with the first full year of operations at FRIB, we have constructed a 2% modest growth budget scenario based on FY23 thousands of dollars, as shown in Figure 12.5. Reductions below FY23-anchored modest growth, such as using FY22 dollars as the baseline, would require further painful reductions.

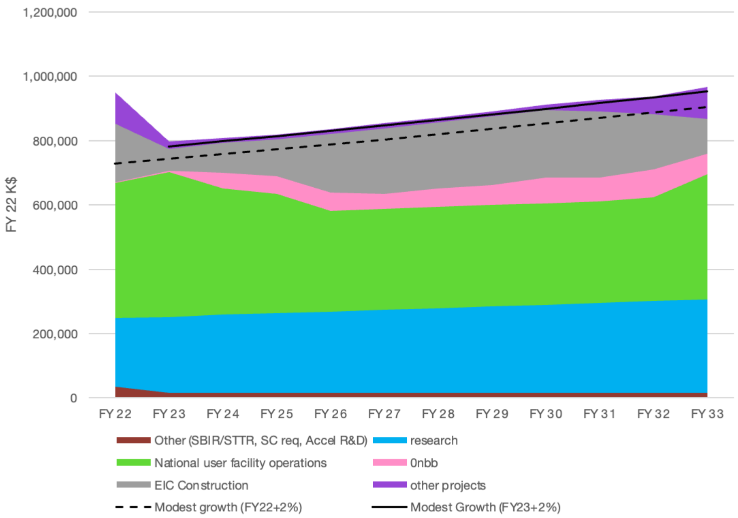


Figure 12.5. Modest growth funding profile. *This funding profile includes the required DOE contributions (e.g., to SBIR/STTR, Accelerator R&D) (brown), funding for a research program at the level of 32% of the enacted FY22 budget (without IRA funds), increasing annually by 2% over inflation (blue), funding for operations of national user facilities at 85% optimal operations (green), funding for the US portion of an international campaign of three ton-scale neutrinoless double beta decay experiments (pink), funding for EIC construction (gray), and funding for other projects (purple). All numbers are in FY22 $K. The solid black line represents modest growth (2% real growth over inflation) anchored by the FY23 enacted budget. The dashed black line represents modest growth (2% real growth over inflation) anchored by the FY22 enacted budget (without IRA funds).*

Under a modest-growth funding scenario, facility operations will suffer. The decrease over current operating hours that Figure 12.5 represents would—if sustained for the entire decade—prevent fully realizing the scientific opportunities of recent investments: the newly commissioned FRIB facility, the largely-IRA funded MOLLER experiment, the world-unique *N* = 126 Factory at ATLAS, and the 12 GeV upgrade at Jefferson Lab, not to mention the potential loss of trained staff. This issue is particularly acute in the case of sPHENIX, because RHIC is projected to complete its science program and stop operations to enable redirection of those operations funds to construction of the EIC. It will also seriously limit the ability to train the next generation of scientists because many nuclear physics doctorates are awarded based on data obtained at the national user facilities. This, though, is the choice the community made in order to maintain US leadership in nuclear physics by building the EIC and next-generation neutrinoless double beta decay experiments and investing in the innovators for tomorrow. We have chosen to pursue those construction projects and reestablish an appropriate equilibrium among research budgets, construction, and operations. The alternative of maintaining operations and constructing these projects and facilities by further eroding the research budget would result in insufficient workforce to fully utilize the facilities and extract the exciting science enabled by new data. Furthermore, limited research budgets would harm the individuals who drive new research ideas, including the graduate researchers, some of whom cannot currently afford basic necessities. They are our future and the nation's future, and we must maintain the ability to develop the technology and workforce for the future through the exciting discovery science of nuclear physics.

Funding at constant effort for the next decade would sacrifice much of the new opportunities presented in this Long Range Plan and result in relinquishing US leadership in key areas of nuclear physics. Additionally, this scenario would be detrimental to national interests by diminishing the pipeline to a STEM workforce from nuclear physics.

Although the preceding discussion has focused on the DOE NP funding for nuclear physics, the NSF is an important partner in achieving the vision laid out in this Long Range Plan. Continued robust NSF funding for the university-based research groups and ARUNA laboratories is essential. We encourage continued NSF funding of undergraduate researchers through the REU and CEU programs. Several high-impact projects discussed in this Long Range Plan could be realized with midscale funding from the NSF.

Nuclear physics can and does deliver science, technology, and people for the nation. While enabling opportunities for all Americans and inviting the participation of international colleagues, the vision laid out in this Long Range Plan will strengthen the US global leadership in nuclear physics and work to sustain national competitiveness. Standing on a strong foundation built on decades of investments, we now reach for the stars. We strive for a greater understanding of the world in which we live to enable both technology and our technically trained innovators to create a greater world. The optimal operation of US national user facilities and university laboratories, a healthy and robust experimental and theoretical core research program, and the pursuit of upgrades and new instruments are now needed to capitalize on previous strategic investments as we embark on a new era of discovery.

Long Range Plan committee

Appendix A: NSAC LRP 2022 Charge Letter

U.S. Department of Energy
and the
National Science Foundation

July 11, 2022

Professor Gail Dodge
Chair, DOE/NSF Nuclear Science Advisory Committee
College of Sciences
Old Dominion University
4600 Elkhorn Avenue
Norfolk, Virginia 23529

Dear Professor Dodge:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long-range plan (LRP) that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade.

The new NSAC LRP should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. nuclear physics program to pursue over the next decade (fiscal year (FY) 2023-2032) and articulate its potential scientific impact. Further, a nationally coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required, including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment, to maintain a world-leadership position in nuclear physics research. The LRP should also describe the potential impacts and priorities under constant level of effort budgets, 2 percent growth per year using the FY 2022 enacted funding level as a reference.

The extent, benefits, impacts, and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the United States (U.S.) and other countries, and of interagency coordination and collaboration in crosscutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. Further, the scientific impacts of synergies with neighboring research disciplines and further opportunities for mutually beneficial interactions with outside disciplines should be discussed. The document should also articulate how efforts to promote and sustain a diverse, equitable, and inclusive nuclear science workforce will be fully integrated into every aspect of the vision for the future of U.S. nuclear science.

In the development of previous LRPs, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (NUCL/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again and to further engage the DNP/APS and NUCL/ACS in laying out the broader issues of contributions of nuclear science research to society.

Please submit your initial report to DOE and NSF by October 2023. The agencies very much appreciate NSAC's willingness to undertake this task. NSAC's previous LRPs have played a critical role in shaping the Nation's nuclear science research efforts. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

Asmeret Asefaw Berhe

Asmeret Asefaw Berhe
Director
Office of Science

Sean L. Jon

Sean L. Jones
Assistant Director
Directorate for Mathematical
and Physical Sciences
National Science Foundation

Appendix B: Town Meetings

2022 Town Hall Meeting on Hot and Cold Quantum Chromodynamics

September 23–25, 2022

Massachusetts Institute of Technology

Conveners:

- Bjoern Schenke (Brookhaven National Laboratory)
- Anne Sickles (University of Illinois)
- Feng Yuan (Lawrence Berkely National Laboratory)
- Xiaochao Zheng (University of Virginia)

Website: https://indico.mit.edu/event/538/

NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions, and Astrophysics

November 14–16, 2022

Argonne National Laboratory

Conveners:

- Alex Gade (Michigan State University)
- Sofia Quaglioni (Lawrence Livermore National Laboratory)
- Grigory Rogachev (Texas A&M University)
- Rebecca Surman (University of Notre Dame)

Website: https://indico.phy.anl.gov/event/22/

Fundamental Symmetries, Neutrons, and Neutrinos Town Meeting

December 13–15, 2022

University of North Carolina at Chapel Hill

Conveners:

- Leah Broussard (Oak Ridge National Laboratory)
- Vincenzo Cirigliano (University of Washington)
- Jon Engel (University of North Carolina at Chapel Hill)
- Lindley Winslow (Massachusetts Institute of Technology)

Website: https://indico.phy.ornl.gov/event/209/

Appendix C: Participants

Long Range Plan Working Group Membership

Christine Aidala, *University of Michigan*
Ani Aprahamian, *University of Notre Dame*
Sonia Bacca, *Johannes Gutenberg-Universität Mainz*
Paulo Bedaque, *University of Maryland*
Lee Bernstein, *Lawrence Berkeley National Laboratory*
Joseph Carlson, *Los Alamos National Laboratory*
Michael Carpenter, *Argonne National Laboratory*
Kelly Chipps, *Oak Ridge National Laboratory*
Vincenzo Cirigliano, *University of Washington*
Ian Cloët, *Argonne National Laboratory*
Andre de Gouvea, *Northwestern University*
Romualdo deSouza, *Indiana University*
Gail Dodge *(Chair), Old Dominion University*
Evangeline J. Downie, *George Washington University*
Jozef Dudek, *William & Mary and Thomas Jefferson National Accelerator Facility*
Renée Fatemi, *University of Kentucky*
Alexandra Gade, *Michigan State University*
Haiyan Gao, *Brookhaven National Laboratory and Duke University*
Susan Gardner, *University of Kentucky*
Senta Victoria Greene, *Vanderbilt University*
Austin Harton, *Chicago State University*
W. Raphael Hix, *Oak Ridge National Laboratory and University of Tennessee, Knoxville*
Tanja Horn, *The Catholic University of America*
Calvin R. Howell, *Duke University*
Yordanka Ilieva, *University of South Carolina*
Barbara Jacak, *University of California, Berkeley and Lawrence Berkeley National Laboratory*
Cynthia Keppel, *Thomas Jefferson National Accelerator Facility*
Oliver Kester, *TRIUMF*
Joshua Klein, *University of Pennsylvania*
Krishna Kumar, *University of Massachusetts Amherst*
Kyle Leach, *Colorado School of Mines*
Dean Lee, *Michigan State University*
Shelly Lesher, *University of Wisconsin–La Crosse*
Chen-Yu Liu, *University of Illinois Urbana-Champaign*
Jorge Lopez, *University of Texas at El Paso*
Cecilia Lunardini, *Arizona State University*
Richard Milner, *Massachusetts Institute of Technology*
Filomena Nunes, *Michigan State University*
Daniel Phillips, *Ohio University*
Jorge Piekarewicz, *Florida State University*
Dinko Počanić, *University of Virginia*
Jianwei Qiu, *Thomas Jefferson National Accelerator Facility*
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Rosi Reed, *Lehigh University*
Lijuan Ruan, *Brookhaven National Laboratory*
Martin Savage, *University of Washington*
Carol Scarlett, *Florida A&M University*
Bjoern Schenke, *Brookhaven National Laboratory*
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Derek Teaney, *The State University of New York at Stony Brook*
Brent VanDevender, *Pacific Northwest National Laboratory and University of Washington*
Ramona Vogt, *Lawrence Livermore National Laboratory and University of California, Davis*
Nathalie Wall, *University of Florida*
Fred Wietfeldt, *Tulane University*
John Wilkerson, *University of North Carolina at Chapel Hill*
Richard Wilson, *Argonne National Laboratory*
Lindley Winslow, *Massachusetts Institute of Technology*
Sherry Yennello, *Texas A&M University*
Xiaochao Zheng, *University of Virginia*

International Observers

Byungsik Hong, *Korea University and ANPhA*
Marek Lewitowicz, *GANIL and NuPECC*

Agency Representatives

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David Cinabro, *DOE*
Latifa Elouadrhiri, *DOE*
Michael Famiano, *DOE*
Manouchehr Farkhondeh, *DOE*
Alfredo Galindo-Uribarri, *NSF*
Ivan Graff, *DOE*
Xiaofeng Guo, *DOE*
Timothy Hallman, *DOE*
Kenneth Hicks, *DOE*
Paul Mantica, *DOE*
Spyridon Margetis, *DOE*
Astrid Morreale, *DOE*
Allena Opper, *NSF*
Paul Sorensen, *DOE*

Appendix D: LRP Resolution Meeting

LRP Resolution Meeting
Westin Hotel, Virginia Beach, Virginia
July 10–14, 2023

Monday July 10

7–8	**Breakfast**	
8:15–8:35	**Welcome, overview of plan for the week (15 + 5)**	Gail Dodge
8:35–8:55	**Introductory remarks from DOE (15 + 5)**	Tim Hallman
8:55–9:15	**Introductory remarks from NSF (15 + 5)**	Allena Opper
9:15–9:40	**Congressional funding context (15 + 10)**	Thomas Glasmacher
9:40–10:10	**Break**	
10:10–11:00	**Neutrinoless double beta decay (30 + 20)**	Vincenzo Cirigliano
11:00–12:10	**Targeted program aimed at challenging the Standard Model**	
	• CP violation: EDM and other observables (15 + 10)	Chen-Yu Liu
	• Precision tests of the SM (20 + 10)	Leah Broussard
	• Properties of neutrinos and hypothetical light particles (10 + 5)	Kyle Leach
12:10–12:40	**FSNN Discussion**	
12:40–2	**Working lunch**	
	• Theory (15 + 15)	Filomena Nunes
	• QIS (15 + 15)	Martin Savage
2:15–3:15	**QCD program overview**	
	• Cold QCD (20 + 10)	Jim Napolitano
	• Hot QCD (20 + 10)	Barbara Jacak
3:15–4:15	**EIC (30 + 30 min)**	
	• Science/Project	Rolf Ent
	• ePIC detector	John Lajoie
4:15–4:45	**Break**	
4:45–5:35	**QCD initiatives (50 min; 5 + 5 for each)**	
	• EIC second detector	Renee Fatemi
	• Polarized positron beam at CEBAF	Thia Keppel
	• Towards an energy upgrade at CEBAF	Thia Keppel
	• LHC detector upgrades and CERN initiatives	Vicki Greene
	• High baryon density frontier	Lijuan Ruan
5:35–6:05	**QCD discussion**	
6:05–8	**Dinner**	
8–	**Evening available for subgroups to work on Long Range Plan document**	

Tuesday July 11

7–8	**Breakfast**	
8:30–9:10	**Nuclear structure and reactions (25 + 15)**	Heather Crawford
9:10–9:50	**Nuclear astrophysics (25 + 15)**	Hendrik Schatz
9:50–10:20	**NSRA program and initiatives**	
	• FRIB400, FDS, ISLA (20 + 10)	Alexandra Gade
10:30–11	**Break**	
11–11:50	**NSRA program and initiatives, continued**	
	• ATLAS (15 + 5)	Guy Savard
	• ARUNA labs (15 + 5)	Ani Aprahamian
	• Research centers (5 + 5)	Sanjay Reddy
11:50–12:30	**NSRA discussion**	

12:30–2	**Working lunch**	
	• HPC (10 + 10)	Raph Hix
	• AI/ML (10 + 10)	Tanya Horn
	• Nuclear data (10 + 10)	Ramona Vogt
2:15–2:45	**Workforce overview and statistics**	Shelly Lesher
2:45–3:15	**DEI initiatives**	Evie Downie
3:15–4	**Discussion**	
4–4:30	**Break**	
4:30–5:30	**International context**	
	• Europe (15 + 5)	Marek Lewitowicz
	• Asia (15 + 5)	Byungsik Hong
	• Canada (15 + 5)	Oliver Kester
5:30–6	**Discussion and homework**	
6–8	**Dinner**	
8–9	**Closed Session: Initial budget presentation and discussion**	Sherry Yennello

Wednesday July 12

Closed Session

7–8	**Breakfast**
8:30–10	**Discussion of recommendations**
10:30–11	**Break**
11–12	**Discussion of recommendations**
12:15	**Group photo**
12:30–2	**Working lunch**
2:30–4	**Discussion of recommendations**
4–4:30	**Break**
4:30–6	**Discussion of recommendations**
6–8	**Dinner**
8–	**Evening available for subgroups to meet**

Thursday July 13

Closed Session

7–8	**Breakfast**
8:30–10	**Discussion of budget scenarios**
10–10:30	**Break**
10:30–11:30	**Budget Discussion, continued**
11:30–12:30	**Other issues; new ideas**
12:30–2	**Working lunch**
2:15–4	**Status of the report and timeline**
4–4:30	**Break**
4:30–6	**Language of recommendations**
6–8	**Dinner**
8–	**Evening available for subgroups to meet**

Friday July 14

Closed Session

7–8	**Breakfast**
8:30–10	**Final language for recommendations/initiatives**
10–10:30	**Break**
10:30–12	**Continue discussion of initiatives/Long Range Plan document**
12–1	**Working lunch**
1	**Adjourn**

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[8] Image adapted from ALICE Collaboration, S. Acharya *et al.*, "Constraining hadronization mechanisms with Λ^+_c /D^0 production ratios in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV," 2023 Phys Lett B 839, 137796, DOI: 10.1016/j.physletb.2023.137796; ALICE Collaboration, S. Acharya *et al.*, "Λ^+_c production in pp and in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV," 2021 Phys Rev C 104, 054905, DOI: 10.1103/PhysRevC.104.054905; and ALICE Collaboration, S. Acharya *et al.*, "Λ^+_c production and baryon-to-meson ratios in pp and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at the LHC," 2021 Phys Rev Lett 127, 202301, DOI: 10.1103PhysRevLett.127.202301.
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[12] Source: R. Abdul Khalek et al., "Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report," 2022 Nucl Phys A 1026, 122447, DOI: 10.1016/j.nuclphysa.2022.122447.
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[14] Sources: (left) A. Accardi et al., "Electron Ion Collider: The Next QCD Frontier", 2014 US Department of Energy, DOI: 10.48550/arXiv.1212.1701. (right) A. R. Abdul Khalek et al., "Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report," 2022 Nucl Phys A 1026, 122447, DOI: 10.1016/j.nuclphysa.2022.122447.
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[16] Source: H. T. Li et al., "Nuclear Matter Effects on Jet Production at Electron-ion Colliders," 2022 SciPost Phys Proc 8, 134, DOI: 10.21468/SciPostPhysProc.8.134.
[17] Image courtesy of E. C. Simpson, Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/.
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[29] Source: John Arrington et al., “The Solenoidal Large Intensity Device (SoLID) for Jefferson Lab 12 GeV, 2023 J. Phys. G: Nucl. Part. Phys. 50, 110501, DOI: 10.1088/1361-6471/acda21.
[30] Source: D.M. Asner et al., “Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation,” 2015 Phys Rev Lett 114, 162501, DOI: 10.1103/PhysRevLett.114.162501.
[31] Data gathered by Lauren McIntosh; Figure courtesy of E. V. Hansen.
[32] Figure courtesy of Michael Thoennessen, “Analysis of Nuclear Physics Faculty Demographics,” presentation to Long Range Planning Workforce Committee, March 2023.
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[41] Source: John Arrington *et al.*, “The Solenoidal Large Intensity Device (SoLID) for Jefferson Lab 12 GeV,” 2023 J. Phys. G: Nucl. Part. Phys. 50, 110501, doi:10.1088/1361-6471.acda21.
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[48] Source: L. Bernstein et al., “Status of US Nuclear Data Program Report from the Nuclear Data Charge Subcommittee of the Nuclear Science Advisory Committee (NSAC-ND),” 2023, Nuclear Science Advisory Committee, https://science.osti.gov/np/nsac/Reports.
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[50] This figure was adapted from the 2018 Annual Meeting of the Society of Nuclear Medicine and Molecular Imaging (SNMMI): https://www.itnonline.com/content/snmmi-image-year-highlights-theranostic-approach-advanced-prostate-cancer; courtesy of Michael Hofman.

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[S7] Source: “R. A. Briceño et al., Isoscalar ππ, K¯K, ηη scattering and the σ, f0, f2 mesons from QCD,” 2018 Phys Rev D 97, 054513, DOI: 10.1103/PhysRevD.97.054513.
[S8] Source: C. C. Chang et al., “A Per-Cent-Level Determination of the Nucleon Axial Coupling from Quantum Chromodynamics,” 2018 Nature 558, 7708, DOI: 10.1038/s41586-018-0161-8.
[S9] Source: L. Altenkor et al., "Heavy Quark Diffusion from 2+1 Flavor Lattice QCD with 320 MeV Pion

Mass,"2023 Phys Rev Lett 130, 231902, DOI: 10.1103/PhysRevLett.130.231902.
[S10] Source: Burkert, V.D., Elouadrhiri, L. & Girod, F.X. "The pressure distribution inside the proton," 2018 Nature 557, 396–399, DOI: 10.1038/s41586-018-0060-z.
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[S40] Source: Appel et al. (Borexino Collaboration), "Improved Measurement of Solar Neutrinos from the Carbon-Nitrogen-Oxygen Cycle by Borexino and Its Implications for the Standard Solar Model," 2022 Phys Rev Lett 129, 252701, DOI: 10.1103/PhysRevLett.129.252701.
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Appendix F: Glossary

accretion: the process of a star gaining material from its binary companion star and trapping it gravitationally

asteroseismology (related: "helioseismology"): the study of seismic waves/vibrations on the surface of a star and what these waves reveal about the structure of the star (Sun)

backgrounds: events or spectra detected by an experiment that are not the intended signal

baryon: a composite subatomic particle with half-integer spin (i.e., a fermion) built from quarks and gluons; the particles making up atomic nuclei—protons and neutrons—are the most familiar baryons

Bayesian statistics: a statistical framework for analyzing data; enables the incorporation of prior information in the analysis

beyond the Standard Model (BSM) physics: phenomena that cannot be explained by the Standard Model of Particle Physics

Big Bang: the initial expansion of the universe from a state of very high temperature; about 3 minutes into this process, nuclei began to form, producing hydrogen, helium, and lithium

Bjorken x: a kinematic variable that can be interpreted as the momentum fraction of the hadron carried by a quark or gluon; used to describe deep inelastic scattering

black hole: a gravitational singularity; black holes are the remnant of violent stellar explosions and are so dense that nothing—including light or other electromagnetic waves—has enough energy to escape their gravitational pull

bolometer: a sensitive detector that measures energy deposited by sensing a temperature-dependent change in electrical resistance

boson: a quantum mechanical particle with integer spin (i.e., 0, 1, 2); the force carriers of the Standard Model, including photons and gluons, are all bosons, as is the Higgs; pions and other mesons are bosons, as are nuclei built from even numbers of nucleons, such as the deuteron and helium-4

breathing mode: another name for certain nuclear resonances that can be described as a movement around a shape, like breathing

Cabibbo–Kobayashi–Maskawa (CKM) matrix: a matrix that quantifies the strength of quark flavor change in weak interactions

charge–parity symmetry: a symmetry in which a system is unaffected by the simultaneous combination of charge and parity symmetry operations, thus exchanging matter with antimatter (and vice versa)

cluster emission: a type of nuclear decay in which clumps of neutrons and protons are emitted; alpha decay of nuclei is the most common example of cluster emission

CNO (carbon–nitrogen–oxygen) cycle: a (series of) catalytic reaction cycle(s) that convert hydrogen to helium; the CNO cycle is the dominant mechanism for hydrogen burning in stars more massive than about 1.5 solar masses and for explosive hydrogen burning in novae

color confinement (also known as confinement): in quantum chromodynamics (QCD), the observation that color-charged particles (such as quarks and gluons) cannot be isolated and, therefore, cannot be directly observed outside of hadrons

Compton scattering: a process in which a real photon scatters elastically off a target such as a nucleon, where the photon serves the role of an external electromagnetic field; such a process can be used to probe the polarizabilities of the nucleon

core-collapse supernova: the collapse and subsequent explosion of a massive star after it has exhausted its nuclear fuel; core collapse supernovae are classified as Type Ib, Ic, or II, depending on the chemical elements present

cross section: a measure of the probability that a specific process will take place in the collision of two particles

D0: a meson with a valence structure of a charm quark and an antiup quark

dark sector: general term used to refer to a collection of hypothetical particles and interactions outside of the Standard Model; an example is dark matter, whose existence is known because of its gravitational influences on things we can see but is dark because it does not emit any radiation we can detect

deep inelastic scattering (DIS): a high-energy scattering process in which an electron (or muon or neutrino) interacts with a constituent of the nucleon, such as a single quark

discovery potential: an assessment of an experiment's chances to make a particular discovery under some specified conditions and/or assumptions

double beta decay: a radioactive decay that emits two electrons (i.e., beta particles) and two antineutrinos; this process is allowed in the Standard Model and has been observed

electric dipole moment (EDM): a measure of the separation of electrical charges within a system; permanent EDMs exhibit a shift in energy in applied electric and magnetic fields in a way that violates both parity and time-reversal symmetries

electron capture reactions: nuclear reactions involving the weak force in which a proton in the nucleus converts into a neutron and releases a neutrino

electroweak interactions: the unified description of two of the four known fundamental interactions of nature (electromagnetism and the weak force)

elemental chain: all the isotopes of a particular chemical element that are bound by the strong force; the chain stretches from the proton dripline to the neutron dripline

EMC effect: an observation that the structure of the nucleon is modified when it is embedded in a nucleus

equation of state: a thermodynamic equation that describes the state of matter under a given set of physical conditions, such as pressure, volume, temperature, or internal energy

fermion: a quantum mechanical particle with half-integer spin (e.g., 1/2, 3/2, 5/2); the quarks and leptons of the Standard Model are all fermions; baryons such as the proton and neutron are fermions, as are all atomic nuclei containing an odd number of nucleons, such as helium-3

first-principles methods: systematically improvable techniques that treat a nucleus of mass number A as a quantum system of A nucleons, each of which interacts with all the others

form factors: functions that characterize the distribution of, for example, charge or current inside a hadron or nucleus, as measured by elastic scattering from that hadron or nucleus; form factors depend on the momentum transfer Q2 to that particle

fundamental symmetry: a symmetry (related: "symmetry") that is intrinsic to the strong, weak, or electromagnetic interactions of the particles in the Standard Model

generalized parton distribution (GPD): a generalization of the parton distribution functions (PDFs) to consider the distribution not only of momentum in the direction of motion of the hadron or nucleus but also of the transverse spatial structure

gluon: the electrically neutral, massless boson that mediates the strong force in quantum chromodynamics (QCD); it carries color charge and cannot be directly observed due to confinement

hadron: a composite subatomic particle made from quarks and gluons that have no net color; all hadrons are either a baryon or a meson

hadronization: the process whereby quarks and gluons knocked out of a hadron acquire other quarks and gluons to form new hadrons

helioseismology (related: “asteroseismology”): the application of precision asteroseismology to the Sun

hydrodynamics (also referred to as fluid dynamics): a branch of science that describes the flow of fluids; it has been successful in describing the dynamics of hot quantum chromodynamics (QCD) media, in particular the quark–gluon plasma

hyperon: a baryon containing at least one strange valence quark; examples include the Λ and Σ baryons, which are somewhat heavier than the proton and neutron

i-process: an intermediate neutron capture process between the slow (s-) and rapid (r-) neutron capture processes

incompressibility: the behavior of nuclear matter at very high nuclear densities, similar to the idea of incompressibility in fluids

inverted ordering: one of two possibilities for the ordering of neutrino masses; it differs from the normal ordering in that the heaviest neutrino in the normal order is the lightest in the inverted order

isomer: a relatively long-lived, low-lying energy level in a nucleus; also referred to as “metastable” states, these states can be populated by thermal excitation or as the end product of a nuclear decay and can possess half-lives that are long with respect to the astrophysical events in which they are synthesized

isospin: a property of hadrons related to up and down quark content; sensitive enough experiments can resolve different interactions for protons and neutrons, known as isospin dependence

jet: a narrow cone of hadrons and other particles produced by the hadronization of a quark or gluon when it is knocked out of a hadron

jet quenching: the energy reduction of a jet, caused by its interaction with the hot medium

kaon: the lightest meson containing a single strange or antistrange valence quark; it has a little more than three times the mass of the lightest meson without strange quarks, the pion

kilonova: the ultraviolet, optical, and infrared afterglow of a neutron star merger

leptons: fundamental particles that are not composed of quarks and gluons and do not experience the Standard Model strong force; electrons, muons, and neutrinos are leptons

lithium problem: the seeming disagreement between the observed abundance of lithium in the oldest stars and the abundance predicted by Big Bang nucleosynthesis calculations

luminosity: a measure that quantifies the number of interactions per second, either with a beam and fixed target or for two colliding beams; it depends on the flux of incident particles and the nature of the target (in a fixed target experiment) or the fluxes of each beam in a collider

magnetic moment: a measure of the strength and orientation of an object that produces a magnetic field

Majorana fermion: a fermion that is its own antiparticle

mean-field model: a model of nuclear dynamics in which each nucleon moves independently in response to a force field that is generated by the combined effect of all the other nucleons

meson: a composite particle with integer spin (i.e., a boson) built from quarks and gluons; the simplest mesons have a valence structure of one quark and one antiquark

metal-poor star: a star with low concentrations of the elements heavier than helium; such stars are generally old, since the concentration of these heavier elements has been increasing throughout the history of the Milky Way Galaxy

multi-messenger: putting into practice complementary information from nuclear reactions, neutrinos, gravitational waves, photons, and cosmic rays in addition to the traditional observational astronomy to better understand the processes of the physical universe

muon: a fundamental lepton, closely related to the electron but with a mass 207 times higher

neutrino: a lepton with very small mass and no electric charge; each charged lepton (electron, muon, and tau) has a corresponding neutrino

neutrino flavor conversion: neutrino oscillations among the three neutrino flavors predicted by the Standard Model (electron, muon, and tau)

neutrinoless double beta decay: a radioactive decay that emits two electrons (i.e., beta particles) and no neutrinos; this process can only occur by physics beyond the Standard Model

neutron: a baryon with a mass only slightly larger than the proton (but without an electric charge) that is present in all atomic nuclei except for hydrogen and is composed of three valence quarks (two down quarks and one up quark) and a sea of quark–antiquark pairs and gluons; free neutrons are unstable with a lifetime of about 15 min, but they can be rendered stable when they are embedded in an atomic nucleus

neutron star crust: the outermost roughly 1 km layer of a neutron star

neutron star: compact objects with masses comparable to that of the Sun but with a radius of about 10–15 km

normal ordering: one of two possibilities for the ordering of neutrino masses; the values follow a hierarchical structure reminiscent of the quarks and charged leptons

nova: cataclysmic variable stars consisting of an accreting white dwarf and a mass-donating companion star, classified into three categories of increasing brightness (correlating with increased recurrence time): dwarf, recurrent, and classical novae; classical novae and many recurrent novae are powered by thermonuclear reactions, whereas the others are powered by irregular accretion

nuclear pasta: a phase of nuclear matter, the signatures of which have been observed in objects such as neutron stars; this matter phase is characterized by dense structures resembling various forms of pasta

nucleon: a generic title referring to a proton or a neutron

pair-instability supernova (also known as pair-production supernova): events predicted to take place when the production of electron–positron pairs from the collisions of gamma rays reduces the internal radiation pressure in the massive star, accelerating the supernova explosion

parity symmetry: a symmetry in which a system is indistinguishable from its mirror image

parity-violating electron scattering (PVES): an experimental technique that allows for measurements where parity symmetry is not obeyed in the scattering of electrons from unpolarized targets, for unique insights into the properties of matter

parton distribution functions (PDFs): functions that describe how the parton's momentum is distributed parallel to the overall momentum of the hadron or nucleus

parton: generic term for any fundamental particle constituent within a hadron; includes valence quarks and antiquarks, sea quarks and antiquarks, and gluons

perturbative quantum chromodynamics (QCD): a theoretical technique taking advantage of the fact that the strength of the strong force decreases at high energies or short distances; when the coupling constant is small enough, a well-defined approximation scheme exists, allowing calculations of quark and gluon interactions to be carried out

photon: massless boson that mediates the electromagnetic force

pion: the lightest known hadron, a meson with a mass about 270 times that of an electron

pointlike: description of fundamental particles (e.g., quarks, gluons, and electrons) that have no known internal structure

polarizability: response of a nucleon to an external electromagnetic field

spin polarization: the degree to which the spin vector of a particle in a beam or a target is aligned with a given direction

positron: antiparticle of the electron, with the same mass but opposite charge

presolar grains (also known as stardust grains): the tiny amounts of material condensed into meteorites that contain isotopic traces of the conditions in which they formed, such as an overabundance of certain isotopes compared with the ratios found on Earth

proton: the nucleus of the hydrogen atom (having positive electric charge equal in magnitude to that of the electron but opposite in sign), composed of three valence quarks (two up quarks and one down quark) and a sea of quark–antiquark pairs and gluons; atomic nuclei are composed of protons and neutrons, and the proton is believed to be stable

proton-emission threshold: the minimum energy that a state in a nucleus needs before it becomes unstable to decay by the emission of one proton

quantum chromodynamics (QCD): the theory of the strong interaction between quarks mediated by gluons, analogous to the quantum theory of electricity and magnetism in many ways, with color charge instead of electric charge; it forms part of the Standard Model of particle physics, describing the binding of quarks and gluons inside composite hadrons (such as the proton, neutron, and pion) and all strong interactions between hadrons (such as those needed to bind protons and neutrons into atomic nuclei)

quark: elementary structureless particles of the Standard Model that carry electric and color charge and interact strongly through gluon exchange, electromagnetically through photons, and weakly through weak bosons; they are never observed in isolation, only as constituents in hadrons, and are currently believed to comprise six flavors (in order of increasing mass: up, down, strange, charm, bottom, and top, with nuclear physics primarily concerned with the lightest two flavors)

quark–gluon plasma (QGP): an equilibrated state of matter in which quarks and gluons are freed from confinement in hadrons, believed to have existed in the early universe and recreated in high-energy collisions

quark–lepton universality: a property of the Standard Model which requires that quarks and leptons experience the weak force with equal strength, up to the effect of the CKM matrix

r-process: the rapid neutron capture process, typified by neutron captures that proceed much more quickly than beta decays, resulting in the creation of highly neutron-rich, short-lived nuclei that then decay back to stability

rp-process: the rapid proton capture process, a nucleosynthetic process that occurs on the proton-rich side of stability; it is typified by a series of proton captures and beta decays that proceed near the N = Z line

RS Ophiuchi: a recurrent nova last observed in 2021 in the constellation Ophiuchus, about 5000 light-years from Earth

s-process: the slow neutron capture process, typified by neutron capture timescales that are slow relative to the beta decay timescale, so the nuclear flow proceeds along the edge of stability

sea quarks: quark–antiquark pairs that are created and destroyed on very short timescales; hadrons have sea quarks in addition to their valence quarks

shape coexistence: the ability of certain nuclei to exist in a superposition of two quantum mechanical states that correspond to different nuclear shapes

spectral neutrino radiation transport: a formalism to describe the physics of neutrinos of different flavors and different energies and their interactions with matter

spectrometer: an instrument that can measure the momentum of charged particles emerging from a subatomic decay or reaction

spin: angular momentum that is an intrinsic property of a particle (i.e., not arising from the actual rotation of mass); electrons, quarks, and nucleons have a spin of 1/2

standard solar model: a mathematical description of the Sun, incorporating hydrostatic equilibrium, energy transport, thermonuclear reactions, and initial conditions

sterile neutrinos: hypothetical neutrinos that participate only indirectly in Standard Model weak interactions

structure function: a function that describes the behavior of hadrons and nuclei in deep inelastic scattering that can be related to their partonic structure

subatomic: the domain of physical size that encompasses objects smaller than an atom; it is the scale at which the atomic constituents, such as the nucleus (containing protons and neutrons) and the electrons (which orbit in paths described by quantum mechanics around the nucleus), become apparent

supernova: the sudden brightening of a star to a luminosity comparable to an entire galaxy; observationally, supernovae are classified into types (e.g., Type Ia, Type Ic, Type IIP), and multiple mechanisms exist (the most common are thermonuclear supernovae, core-collapse supernovae, and pair-production supernovae)

symmetry: a transformation that leaves a physical system unchanged

symmetry violation: a phenomenon in which a symmetry is not realized in a system

tensor interaction: a hypothetical interaction named for its mathematical transformation properties; tensor interactions are not included in the Standard Model but are a common feature of theories beyond the Standard Model

thermonuclear supernova: a type of supernova (compared with core-collapse supernovae) occurring in binary star systems and triggered by the thermonuclear runaway of accreted material on their surface

tidal deformation: the changes in shape away from spherical experienced by an astronomical body caused by tidal (gravitational) forces

time-projection chamber: an advanced detector capable of reconstructing particle trajectories in three dimensions

time-reversal symmetry: a symmetry in which the description of a system is unaffected by the direction of time

ton-scale neutrinoless double beta decay experiment: an experiment deploying isotopic mass of sufficient size to discover neutrinoless double beta decay if neutrinos are Majorana fermions with masses of 10–20 meV or greater

transverse momentum distribution (TMD): parton distribution functions in 3D momentum space with two dimensions transverse to and one along the motion of the hadron

triton: an isotope of hydrogen with two neutrons and one proton; it is the most neutron-rich isotope of hydrogen and decays to helium-3 by beta emission

ultrahigh-energy cosmic rays (UHECR): cosmic rays observed with energies above 1018 eV

ultracold neutrons (UCNs): a population of low-energy neutrons characterized by a temperature of a few millikelvin or less (i.e., a mean energy of a few hundred nanoelectronvolts) that can be stored in a trap

Urca process: a process by which nuclear reactions emit neutrinos and thus enhance the cooling of neutron star crust material, named after the Cassino de Urca in Rio de Janeiro

valence quarks: the quarks and antiquarks required to describe the properties of a hadron; for example, the valence quarks in the proton are uud (two up quarks and one down quark)

viscosity: a measure of a fluid's resistance to deformation; shear viscosity is resistance to shear stress, whereas bulk viscosity is resistance to the shearless compression or expansion of a fluid

vorticity: a measure of the local rotation of fluid elements in a flow field

weak interaction (also known as weak force): one of the fundamental interactions (or forces) of the Standard Model

x-ray bursts: the recurrent thermonuclear explosion of accreted hydrogen- and helium-rich material on the surface of a neutron star, releasing x-rays

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THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

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