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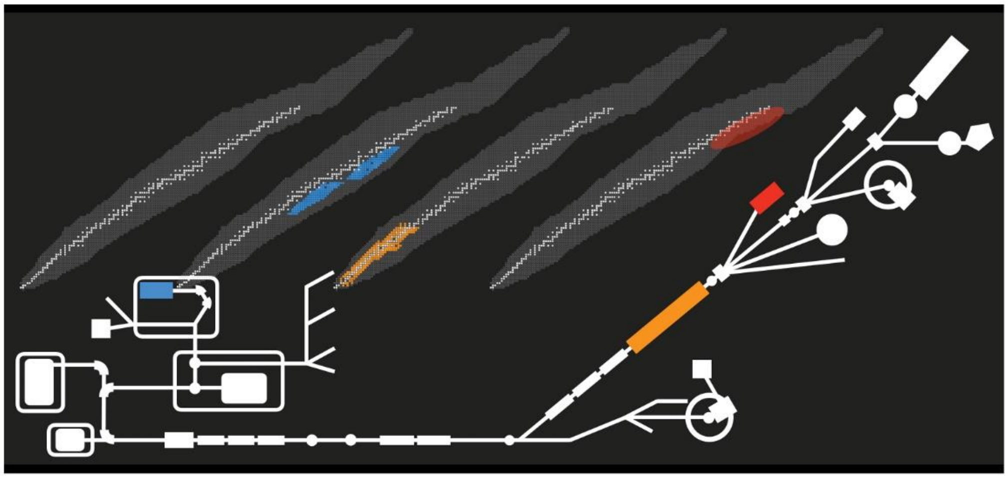
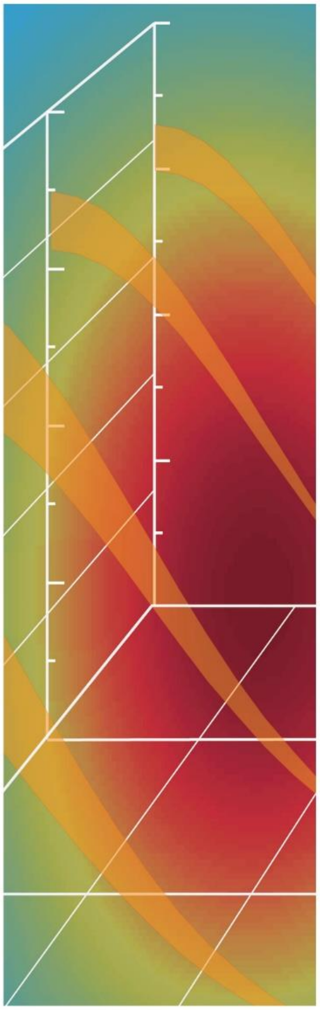
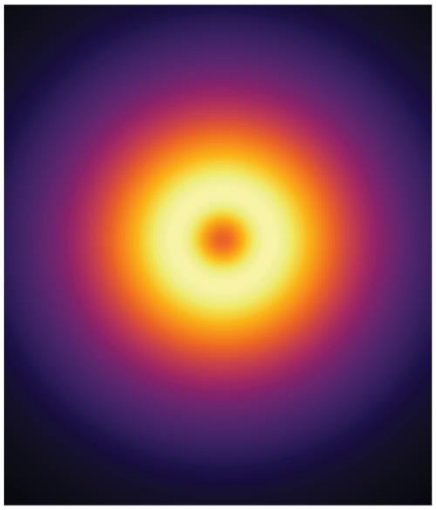
PHYSICS DIVISION

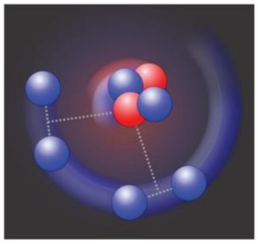
STRATEGIC PLAN

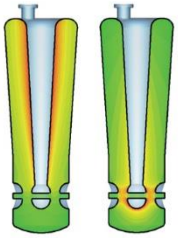
Fiscal Years 2020–2024

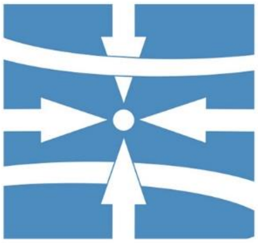


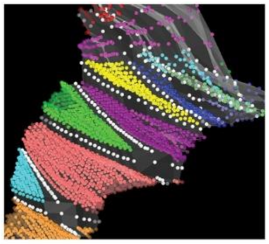












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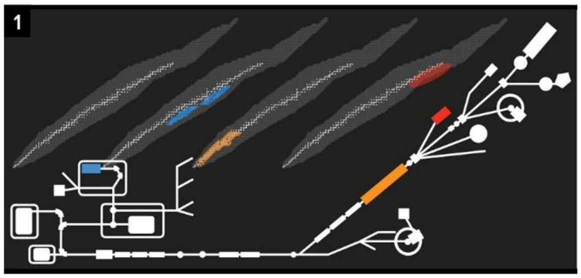

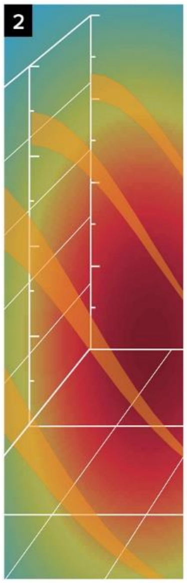

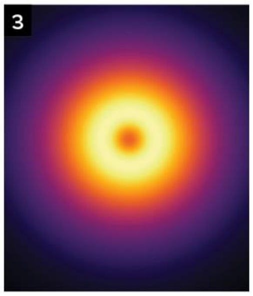

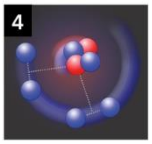

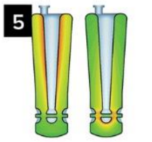

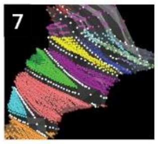

1. Abstract representation of ATLAS facility and isotopes produced. (Image by Ben Kay, Argonne National Laboratory.)
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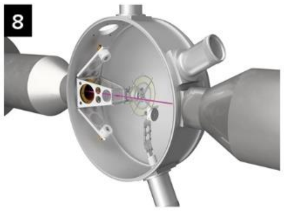

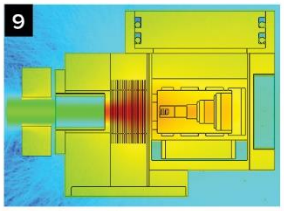

8. Rotating target system inside Gammasphere. (Image by Russell Knaack, Argonne National Laboratory.)
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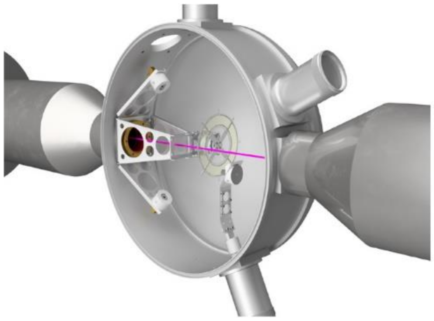
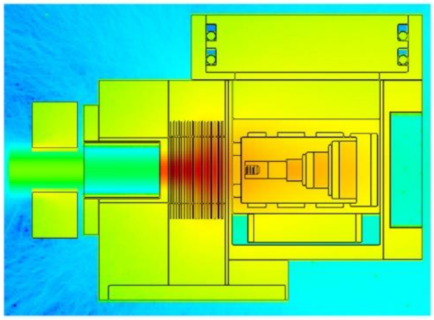
PHYSICS DIVISION

STRATEGIC PLAN





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List of Acronyms

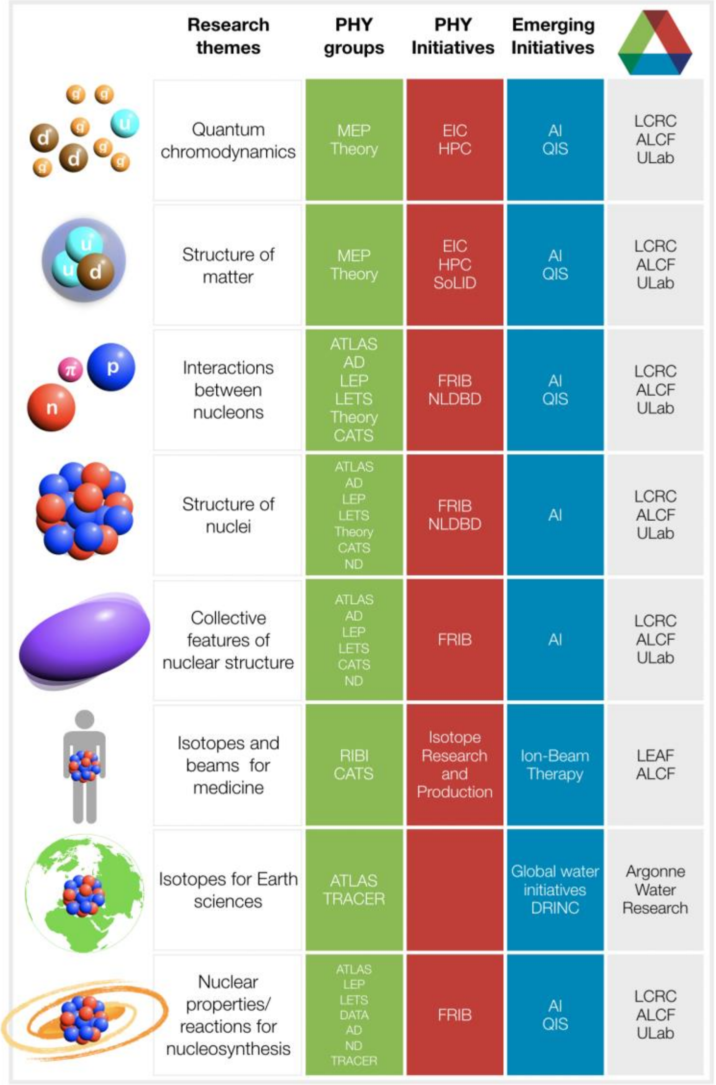
ACCIL	Advanced Compact Carbon Ion Linac
AD	Accelerator Development
AFDMC	Auxiliary Field Diffusion Monte Carlo
AGFA	Argonne Gas Filled Analyzer
AI	Artificial Intelligence
AIP	Accelerator Improvement Project
ALCF	Argonne Leadership Computing Facility
ALERT	Low Energy Recoil Tracker
AME	Atomic Mass Evaluation
APS	Advanced Photon Source
ASCR	Advanced Scientific Computing Research
ATLAS	Argonne Tandem Linac Accelerator System
ATTA	Atom Trap Trace Analysis
BPT	Beta-Paul Trap
CARIBU	Californium Rare Isotope Breeder Upgrade
CATS	Center for Accelerator Target Science
CLAS12	CEBAF Large Acceptance Spectrometer (for 12 GeV)
CVMC	Cluster Variational Monte Carlo
CT	Computer Tomography
CVMC	Cluster Variational Monte Carlo
DOE	U.S. Department of Energy
DOE-NP	U.S. Department of Energy, Office of Science, Office of Nuclear Physics
DRL	Deep Reinforcement Learning
DUNE	Deep Underground Neutrino Experiment
EBIS	Electron Beam Ion Source
ECR	Electron Cyclotron Resonance
EDM	Electric Dipole Moment
EFT	Effective Field Theories
EIC	Electron-Ion Collider
ENSDF	Evaluated Nuclear Structure Data File
EoS	Equation of State
FRIB	Facility for Rare Isotope Beams
GFMC	Green's Function Monte Carlo
GRETINA	Gamma-Ray Tracking In-beam Nuclear Array
GRETA	Gamma-Ray Tracking Array
HELIOS	Helical Orbit Spectrometer
HPC	High-Performance Computing
HQMC	Hybrid Quantum Monte Carlo
INFN	Italian Institute of Nuclear Physics
KARMEN	Karlsruhe Rutherford Medium Energy Neutrino
LAPPDs	Large-Area Picosecond Photon Detectors
LCRC	Laboratory Computing Resource Center
LDRD	Laboratory Directed Research and Development
LEAF	Low Energy Accelerator Facility
LEP	Low Energy Physics
LET	Linear Energy Transfer
LETS	Low Energy Technical Support
LSND	Liquid Scintillation Neutrino Detector
MEP	Medium Energy Physics
MUSE	MUon Proton Scattering Experiment
NAS	National Academies of Sciences, Engineering, and Medicine
NCSL	National Superconducting Cyclotron Laboratory
ND	Nuclear Data Program
NEXT	Neutrino Experiment with Xenon Time Projection Chamber
NLDBD	Neutrinoless Double Beta Decay
NP	Nuclear Physics
NSAC	National Science Advisory Committee
NUCLEI	Nuclear Computational Low-Energy Initiative
PET	Positron Emission Tomography
PHY	Physics Division
PSA	Prostate Specific Antigen
QCD	Quantum Chromodynamics
QMC	Quantum Monte Carlo
QIS	Quantum Information Science
R2P2	Radioisotope Research and Production Program
RAISOR	Argonne In-flight Radioactive Ion Separator
RBE	Relative Biological Effectiveness
RIBI	Research with Ion Beams and Isotopes
SATURN	Scintillator and Tape Using Radioactive Nuclei
SBIR	Small Business Innovation Research
SciDAC	Scientific Discovery through Advanced Computing
SOLARIS	Solenoidal Spectrometer Apparatus for Reaction Studies
SoLID	Solenoidal Large Intensity Device
TPC	Time Projection Chamber
TRACER	Trace Radioisotope Analysis
ULab	Universe of a Laboratory
USNDP	U.S. Nuclear Data Program
XMAT	Extreme Materials beamline at the Advanced Photon Source

Executive Summary

The vision of the Physics Division (PHY) at Argonne National Laboratory is to continue enhancing its role as a world-leading institution in basic nuclear physics research and its applications. Key to this vision is for PHY to continue to safely and effectively operate and evolve the capabilities of the Argonne Tandem Linac Accelerator System (ATLAS) facility to best serve its users. ATLAS is the Department of Energy (DOE) accelerator facility for low-energy nuclear physics research. The research carried out by PHY covers many themes in contemporary science but can be distilled into five areas of focus. These themes are interconnected, with continuously evolving synergies between the various groups and facilities in PHY and the broader Laboratory. This five-year strategic plan serves to illustrate our current capabilities and new directions related to these five areas of focus (ATLAS also develops an independent strategic plan):

- **Accelerator research and design.** The goal of this theme is to design, fabricate, test, and implement novel accelerator systems, with a focus on high-intensity ion and electron systems. These R&D activities have led to enhancements in the ATLAS accelerator system. Among others, the division's accelerator systems are in use or planned for use at Fermilab, the Advanced Photon Source, and in a broad variety of applications at the Facility for Rare Isotope Beams (FRIB).
- **Atom trapping and fundamental symmetries.** The goal of this theme is to explore and exploit the uses of advanced laser cooling and trapping techniques to manipulate atoms. There are three main areas of focus. First is in the application of the atom trap trace analysis (ATTA) technique for age determination of groundwater and ice by using radio-krypton dating. The next two trapping-based programs involve tests of fundamental symmetries in nature: the cooling and trapping of radium-225 with the aim of determining limits on an observation of its electric dipole moment and precision measurements of the beta decay properties of helium-6 to set limits on the tensor coupling constant. This is complemented by measurements of similar properties in lithium-8 and boron-8.
- **Nuclear astrophysics.** The goal of this theme is to enhance our understanding of how elements are created in the universe via explosive nucleosynthesis and how stars evolve. To meet the challenges of this theme, many of the capabilities of ATLAS are being enhanced, including the development of new beams through a new in-flight separator (RAISOR) and the anticipated neutron-generator upgrade of the Californium Rare Isotope Breeder Upgrade facility (nuCARIBU). These are coupled to state-of-the-art instruments such as the Canadian Penning Trap, Helical Orbit Spectrometer, Gammasphere, GRETINA, Multi-Sampling Ionization Chamber, the Fragment Mass Analyzer, and Argonne Gas-filled Fragment Analyzer, and a new low-background experimental area for decay studies.
- **Nuclear structure.** The goal of this theme is to understand the structure of nuclei, both stable and radioactive, in terms of single-particle properties, their shapes, and the dynamics governing reactions between them. These include questions such as what are the limits of nuclear stability and what are the properties of super heavy nuclei. As with the nuclear astrophysics theme, the capabilities of ATLAS, guided by the ATLAS user community, are continuously being enhanced to this end. The Division has strategic initiatives to play a leading role in the development of instrumentation and research programs at the FRIB.
- **Quantum chromodynamics (QCD) and hadron physics.** The goal of this theme is to lead major research programs focused on revealing the quark and gluon structure of protons, neutrons, nuclei, and short-lived mesons and baryons. These involve major programs at Jefferson Lab, Fermilab, and smaller facilities. They are complemented by theoretical endeavors centered on the question of how hadrons and their properties emerge from QCD. Out of these activities arise strategic initiatives to play a major role in the forthcoming Electron-Ion Collider (EIC).

PHY researchers continue to lead in many DOE programmatic missions. Beyond ATLAS, PHY has developed, operates, and continues to enhance several other local facilities. These include the Center for Accelerator Target Science (CATS), which serves ATLAS, ATLAS users, and the broader low-energy nuclear physics community in producing isotopic targets. It also serves as an R&D center for the development of specialist targets and the training of future generations of scientists. The Accelerator Development group operates the Accelerator Development and Test Facility, a dedicated facility for the development of new accelerator capabilities for ATLAS and many other facilities around the world. Finally, the Argonne Trace Radioisotope Analysis (TRACER) Center has been developed to advance the science of krypton dating for age determination of groundwater and ice.



Research themes	PHY groups	PHY Initiatives	Emerging Initiatives	
Quantum chromodynamics	MEP Theory	EIC HPC	AI QIS	LCRC ALCF ULab
Structure of matter	MEP Theory	EIC HPC SoLID	AI QIS	LCRC ALCF ULab
Interactions between nucleons	ATLAS AD LEP LETS Theory CATS	FRIB NLDBD	AI QIS	LCRC ALCF ULab
Structure of nuclei	ATLAS AD LEP LETS Theory CATS ND	FRIB NLDBD	AI	LCRC ALCF ULab
Collective features of nuclear structure	ATLAS AD LEP LETS CATS ND	FRIB	AI	LCRC ALCF ULab
Isotopes and beams for medicine	RIBI CATS	Isotope Research and Production	Ion-Beam Therapy	LEAF ALCF
Isotopes for Earth sciences	ATLAS TRACER		Global water initiatives DRINC	Argonne Water Research
Nuclear properties/ reactions for nucleosynthesis	ATLAS LEP LETS DATA AD ND TRACER	FRIB	AI QIS	LCRC ALCF ULab

Figure ES-1: The research interests of the Physics Division. The groups and facilities active in these areas are Accelerator Development (AD), Low Energy Physics (LEP) and Technical Support (LETS), Medium Energy Physics (MEP), Theory, Center for Accelerator Target Science (CATS), Research with Ion Beams and Isotopes (RIBI), and Nuclear Data (ND). The strategic initiatives covered include the Electron-Ion Collider (EIC), High-Performance Computing (HPC), Facility for Rare Isotope Beams (FRIB), and Neutrinoless Double Beta Decay (NLDBD). The emerging initiatives covered include Artificial Intelligence (AI) and Quantum Information Science (QIS). Also indicated is how PHY integrates with the Lab through the Universe as a Laboratory (ULab) initiative, Laboratory Computing Resource Center (LCRC), Argonne Leadership Computing Facility (ALCF), and Low-Energy Accelerator Facility (LEAF). (Image by Argonne National Laboratory.)

Over the last few years, many new strategic initiatives have come to the fore, guided by the 2015 Long Range Plan for Nuclear Physics. One is to play a major role in FRIB through instrumentation and research programs. The completion and exploitation of FRIB is one of the top priorities for U.S. nuclear physics. The division is also taking a multifaceted approach to the EIC, with detector and accelerator R&D, theoretical guidance, and simulation and software. Activities at Jefferson Lab include a key role in the proposed Solenoidal Large Intensity Device experiment. A determination of whether neutrinoless double beta decay occurs in Nature is a long-standing challenge in contemporary physics. The division is designing a unique high-pressure xenon time-projection chamber to push next generation technology. Many groups in PHY plan on pushing the limits of high-performance computing in processing real-time data at ATLAS and elsewhere and pushing the limits of theoretical calculations. The division aims to make major inroads into these key challenges in the next five plus years. There are several emerging initiatives, where PHY staff have started to invest heavily in exploring their potential: artificial intelligence, extreme materials, medical isotope research and production, ion-beam therapy, and quantum information science. These emerging initiatives overlap with the DOE portfolio of research and Argonne strategic initiatives.

The Physics Division and ATLAS comprises about 125 staff, approximately 30 of which hold PhDs, together with many postdocs and students. The ATLAS facility hosts 200-300 users per year. The Division has a budget of around $32M per year, of which $21M supports ATLAS directly.

1. Overview of Physics Division

The Physics Division (PHY) at Argonne National Laboratory conducts world-leading research across a spectrum of areas within nuclear physics and more broadly. It operates the Argonne Tandem Linac Accelerator System (ATLAS), which is currently the only U.S. Department of Energy (DOE) national user facility for low-energy nuclear physics. ATLAS provides the low-energy nuclear physics community with high-intensity stable beams, unique radioactive beams, and state-of-the-art experimental equipment to study nuclear structure, nuclear astrophysics, and nuclear data. The facility is supported by a strong group in accelerator R&D and detector design and construction. The division is also the home to exceptional research groups in low energy physics, medium energy physics, and theory. These groups consistently rank highly in national reviews of the DOE nuclear physics program and provide leadership to the U.S. and international nuclear physics communities.

The Physics Division and Argonne have many critical strengths and unique programs that enable a world-leading research program in nuclear physics. The Lab has many core capabilities that support PHY. These include:

- Nuclear physics
- Accelerator science and technology
- Large-scale user facilities and advanced instrumentation
- Nuclear chemistry
- Advanced computer science, visualization, and data
- Computational science
- Particle physics

where the first four of these Argonne core capabilities have significant contributions from PHY. In addition, we benefit from Argonne's major research facilities, such as:

- Argonne Tandem Linac Accelerator System (ATLAS)
- Argonne Leadership Computing Facility (ALCF)
- Center for Nanoscale Materials (CNM)
- Advanced Photon Source (APS)

The Physics Division increases and broadens its impact by taking advantage of the expertise and infrastructure at Argonne, through use of these facilities and collaboration with other divisions, e.g., High-Energy Physics, Materials Science, Nuclear Engineering, Data Science and Machine Learning, and Accelerator Systems at the APS. These have allowed us to enhance our contribution to the national nuclear physics program, while also supporting research on isotope production, radioisotope dating, novel detectors, radiation damage of materials and cells, and support for accelerator projects in high-energy physics, basic energy sciences, cancer treatment, and national security.

The Physics Division's mission is strongly aligned to the national nuclear physics priorities and Argonne's mission to advance science and deliver impact in both discovery and applications. This strategic plan has been assembled to pave a way towards maximum impact in our scientific mission, capitalizing on the strengths of the division together with the supporting resources and scientific/technical expertise of the wider Argonne community.

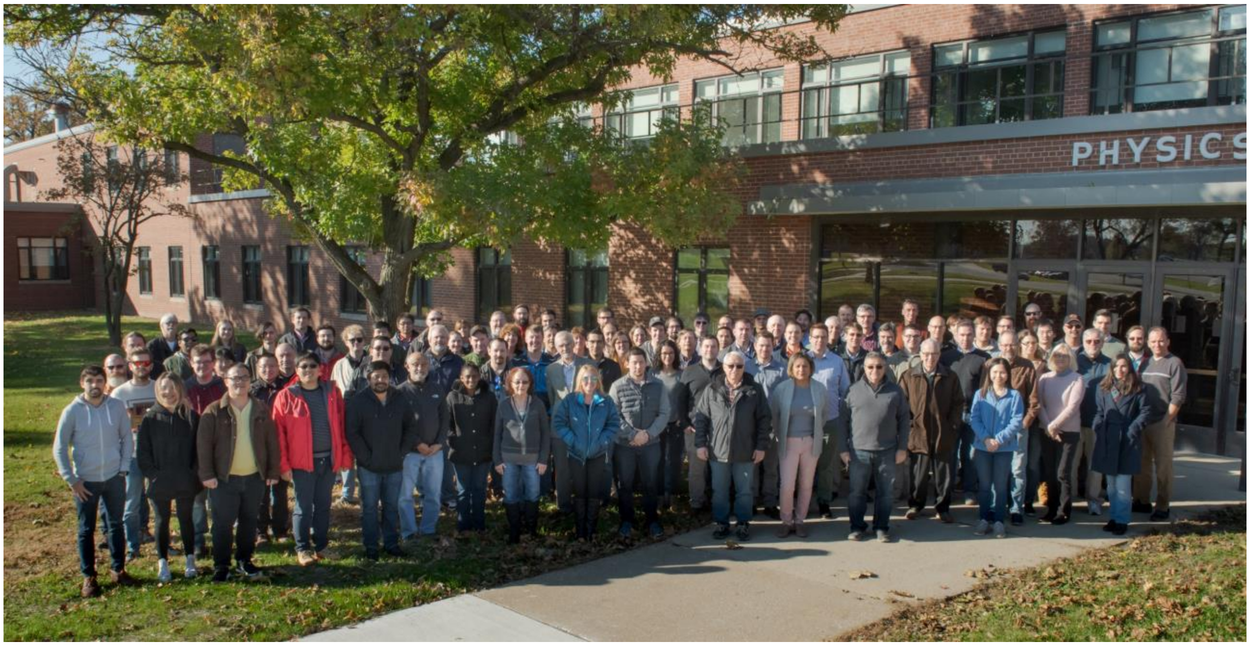
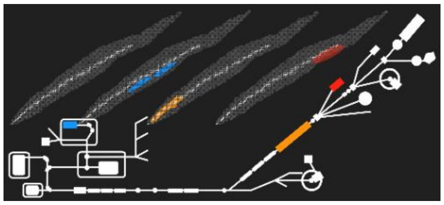


Figure 1-1: Physics Division in October 2019. (Image by Argonne National Laboratory.)

The optimization of our scientific program is tailored to strongly support the national nuclear physics priorities, through support of the major DOE Nuclear Physics (NP) facilities (e.g., ATLAS, Jefferson Lab, and the Facility for Rare Isotope Beams) and priorities (e.g., neutrinoless double beta decay, quantum information sciences, and artificial intelligence), and as expressed by the vision presented in the 2015 Long Range Plan for Nuclear Science and elsewhere.

The starting point for the development of this five-year strategic plan is the resources and expertise available in PHY. Exceptional research groups in low energy, medium energy, and theory form the core of our research efforts, while the ATLAS facility, accelerator development group, and technical support group enable a unique and world-leading program in nuclear structure, nuclear astrophysics, and nuclear data. These programs are already well aligned with the DOE-NP priorities; however, we also plan to take full advantage of important new opportunities for the NP community, such as quantum information science and artificial intelligence. In this way, the Physics Division will enhance its contributions to the DOE-NP program by broadening its leadership into new areas of importance to DOE-NP and the Nation. The Physics Division will enhance the DOE-NP investment by taking maximum advantage of Argonne’s infrastructure and unique facilities. In addition, we will continue to explore and create opportunities to take novel ideas and technologies developed in support of the DOE-NP mission and apply them to the broader DOE mission and Argonne priorities. In the following, we provide a brief overview of the various research groups and facilities in PHY.

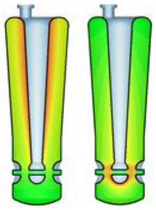
ATLAS



ATLAS is the DOE national user facility for low-energy nuclear physics. It provides high-intensity stable beams at energies in the proximity of the Coulomb barrier. It also provides access to a suite of unique radioactive ion beams via the in-flight production technique and from the Californium Rare Isotope Breeder Upgrade (CARIBU) facility. This is the energy domain ideally suited to study the properties of the nucleus, the core of matter, and the fuel of stars.

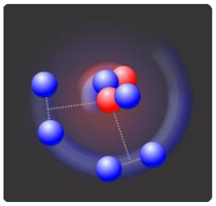
ATLAS hosts roughly 200 to 300 users each year, which come from U.S. universities and national laboratories as well as from foreign institutions. The facility is also accessible to commercial users.

Accelerator Development



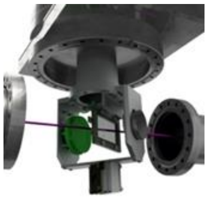
The Accelerator Development group specializes in radio-frequency superconductivity for accelerators and is a recognized world leader in the application of this technology to ion accelerators. Our accelerator physicists are conducting a broad range of R&D projects to establish key technologies for the Facility for Rare Isotope Beams (FRIB), the future Electron-Ion Collider (EIC), the Advanced Photon Source Upgrade (APS-U), and the Proton Improvement Project 2 (PIP2) at Fermilab. They also play a key role in supporting and enhancing the ATLAS facility.

Low Energy Research



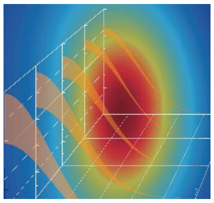
The Low Energy Physics group strives to understand the structure and stability of the nuclei around us and in the cosmos, to explore their astrophysical origin, and to use nuclei as sensitive probes in searches for new physics. The scientific questions guiding this research are: What are the limits of nuclear stability? What are the mechanisms responsible for shell evolution in nuclei? What are the astrophysical processes of nucleosynthesis and which nuclear properties are key to their understanding? What is the physics beyond the Standard Model?

Low Energy Technical Support



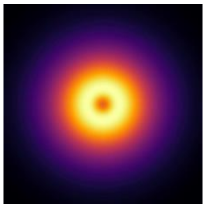
The Low Energy Technical Support (LETS) group supports the local and user research programs at ATLAS, as well as other facilities and larger community-driven activities, such as the Gamma-Ray Energy Tracking Array and Solenoid Spectrometer Apparatus for Reaction Studies. The LETS group, composed of electrical, mechanical, and controls engineers and detector specialists, is involved in all aspects of detector design, fabrication, implementation, and testing. Locally, these include the Argonne Gas-filled Fragment Analyzer, Fragment Mass Analyzer, Gammasphere, Multi-Sampling Ionization Chamber, and Helical Orbit Spectrometer.

Medium Energy Physics



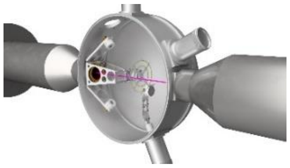
The Medium Energy Physics group studies the structure of hadronic matter and nuclei in terms of its constituents within quantum chromodynamics and looks for signatures of physics beyond the Standard Model. To accomplish this, the group develops and exploits new technologies for high-impact applications in nuclear physics experiments. Major research activities in hadronic and nuclear physics focus on a broad Argonne-led program at Jefferson Lab and the future EIC, supplemented with an in-house program to develop novel particle detectors and to measure the electric dipole moment of radium-225.

Theory



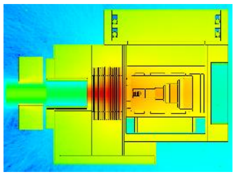
The Theory group addresses key questions that comprise the Nation’s nuclear physics agenda. We place strong emphasis on the prediction of phenomena accessible at facilities in the United States and worldwide, e.g., ATLAS, FRIB, Fermilab, Jefferson Lab, the Large Hadron Collider, and the Relativistic Heavy Ion Collider. We play a key role in the Argonne Strategic Initiative in EIC science by providing predictions for the tomography of hadrons and nuclei, the results of which influence detector design and proposed experiments. We also employ quantum chromodynamics to explore hadron properties in vacuum and in medium, together with the partonic structure of nuclei. We apply *ab initio* methods to study nuclear structure and reactions within the basic model of nuclear physics.

Center for Accelerator Target Science



The Center for Accelerator Target Science (CATS) is the creation of a national center for target science based on the existing target development laboratory at Argonne. The most important and primary CATS mission is to provide dedicated support of the ATLAS scientific program — supplying experimental targets, foils, windows, radioactive sources, and isotopic material for beam production.

Research with Ion Beams and Isotopes

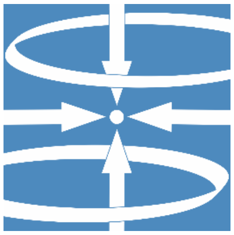


This new interdisciplinary research group was established to initiate new research programs at ATLAS aimed at leveraging the capabilities of the staff and facilities in the Physics and other Argonne divisions to serve communities beyond those focusing on the base mission of DOE-NP. This group is part of the Argonne Radioisotope Research and Production Program, which is a cross-directorate initiative under the DOE Isotope Program and presently produces the medical isotope Cu-67 at the Low Energy Accelerator Facility (LEAF) for sale and distribution to end users through the National Isotope Development Center, the business office of the DOE Isotope Program.

Nuclear Data

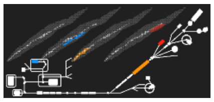
The Nuclear Data Program contributes to the compilation and evaluation of nuclear data for the databases of the DOE-NP sponsored U.S. Nuclear Data Program. Contributions are also made to specialized databases that serve specific needs in the fields of nuclear structure, reactions, nuclear astrophysics, and applied nuclear physics. The Nuclear Data Program also plays a role in experimental activities at the ATLAS and CARIBU facilities, with an emphasis on nuclear structure physics and astrophysics.

TRACER (Trace Radioisotope Analysis) Center



Argonne’s TRACER Center is advancing the science of atom trap trace analysis (ATTA) of noble gas radioisotopes and pioneers novel applications of this technique. ATTA is an extremely sensitive isotopic analysis method invented at Argonne that employs laser-based atom traps to selectively capture and detect isotopes of interest. This technique enables applications such as radio-krypton dating of ancient groundwater and glacial ice. TRACER now offers these analysis capabilities to the Earth science community on a routine basis.

2. Argonne Tandem Linac Accelerator System



The Argonne Tandem Linac Accelerator System (ATLAS), as mandated by the DOE, develops its own strategic plan when the need arises, which is typically about every 4-5 years. The latest one of these was done in the fall of 2018 jointly with the ATLAS user community and the Physics Division. In this section, an overview of the facility and its operation is given along with highlights and extracts from the ATLAS Strategic Plan (https://www.anl.gov/atlas/strategic-plan).

2.1. Introduction

ATLAS is the DOE low-energy nuclear physics national user facility. ATLAS provides high-intensity stable beams and some unique radioactive beam capabilities at low energies and at energies in the proximity of the Coulomb barrier. Coupled with state-of-the-art instrumentation, ATLAS enables users to carry out world-leading research. Instrumentation includes Gammasphere, Fragment Mass Analyzer (FMA), Californium Rare Isotope Breeder Upgrade (CARIBU), Helical Orbit Spectrometer (HELIOS), Argonne Gas Filled Analyzer (AGFA), and Argonne In-flight Radioactive Ion Separator (RAISOR). The Electron Beam Ion Source (EBIS) became operational in 2018 (Figure 2-1).

A floorplan of the ATLAS facility and its experimental areas is shown in Figure 2-2. ATLAS delivers a large number of beam hours for users. An example of some of the operations statistics is given in Figure 2-3. It has been typical over the last five years to deliver about 6000 hours of accelerated beam per year for users. This is around 250 days or 35 weeks, and the data show that it amounts to a unique beam and energy each week. Stable beams dominate the beam schedule (about 80% at present), but as the strategic plans laid out below shows, there is an increasing demand for weaker radioactive ion beams, of which ATLAS has unique capabilities. Independent of the accelerated beams, the CARIBU facility has provided low energy fission fragments for researchers for about 2000 additional hours per year over the last five years. Each year about 200-300 unique researchers carry out experiments at ATLAS at six target stations using both local instruments and those provided

Goals:

- Maintain operational excellence, delivering the requested beam-hours for the community.
- Realize the full potential of the in-flight produced radioactive ion beams with the new RAISOR separator.
- Implement radioactive ion beam diagnostics and beam tracking.
- Build, implement, and operate the $N = 126$ factory.
- Upgrade the CARIBU facility to allow for research with neutron-induced fission fragment beams.
- Develop the new “Area 1” space to house multiple beamlines and Gammasphere.
- Develop multi-user capabilities, to allow simultaneous measurements in different areas with beams at energies around the Coulomb barrier.
- Install a high-current electron cyclotron resonance (ECR) ion source.
- Reaccelerate extremely neutron-rich ion beams produced by the $N = 126$ factory.
- Complete replacement of split-ring cryostats.

Figure 2-1: The Electron Beam Ion Source (EBIS) at ATLAS that became operational in 2018. (Image by Mark Lopez, Argonne National Laboratory.)

by the community, including the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA). Beam time is allocated based on the recommendation of the ATLAS Program Advisory Committee — a panel of leading experts in the fields of low-energy experimental and theoretical nuclear physics, nuclear astrophysics, and applied nuclear science — to the ATLAS Director. The users of ATLAS comprise researchers from laboratories and universities drawn from across the globe.

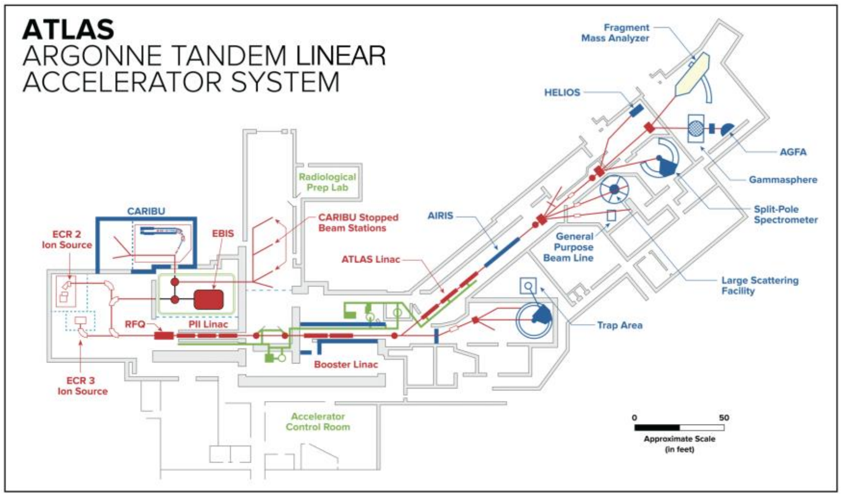


Figure 2-2: Layout of the ATLAS facility. (Image by Argonne National Laboratory.)

The capabilities of ATLAS are continuously evolving to better fulfill the needs of its user community. To this end, the ATLAS strategic plan serves to provide a cogent path forward for the facility, with a coherent vision for the development of accelerator capabilities, experimental equipment, and operations. This is driven by the scientific questions of the low-energy nuclear physics community. The ATLAS strategic plan is developed with community input and with guidance from the National Science Advisory Committees' Long-Range Plan for Nuclear Science. A draft of the 2018 ATLAS Strategic Plan was presented to the ATLAS user community at the 2018 Low Energy Community Meeting. The draft plan was strongly endorsed, with a unanimous resolution stating *"We strongly endorse the vision expressed in the draft ATLAS Strategic Plan for the future of the ATLAS facility and the proposed development of accelerator- and equipment-related initiatives that will enhance the scientific reach and efficient utilization of the ATLAS facility. These initiatives include the upgrade of ATLAS to provide multi-user capabilities which should be supported at a sufficient staffing level for its efficient operation*." The draft plan has subsequently been enacted. The major research themes driving the experimental program at ATLAS are discussed below along with key scientific goals designed to address these. The requirements necessary of the ATLAS facility, its instrumentation, operation, and planned initiatives are given in section 2.2, responding directly to these needs.

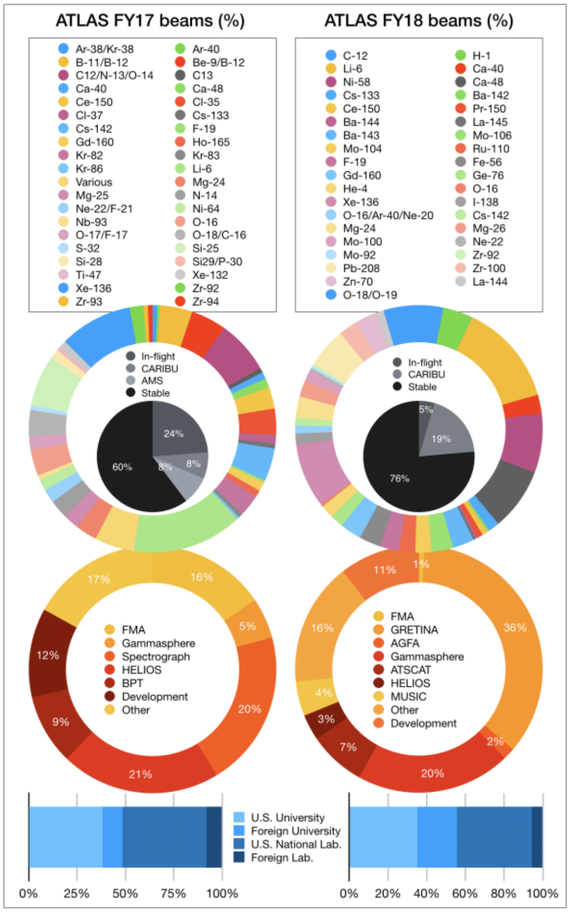


Figure 2-3: ATLAS statistics for FY17 and FY18 by beam species, type, instruments used, and user institutions. (Image by Argonne National Laboratory.)

Research themes	Scientific goals defined by ATLAS users
1. Understanding the structure of nuclei as a many-body system built of protons and neutrons bound by the strong force	Comparisons of the properties of light nuclei ($A<20$) with *ab initio* calculations
	Study of the evolution of single-particle structure from light- to medium-mass nuclei
	Exploration of the properties of neutron-rich nuclei such as changes in shell structure, pairing, single-particle strength, and new types of collective excitations
	Study of the impact of weak binding on the structural properties of nuclei at the proton drip line and beyond, including in the direct vicinity of Sn-100
	Study of the structure of nuclei with $Z>100$ as a challenging test of theories
	Study of the properties of the nuclei at the highest spins and excitation energies
2. Exploring the origin of the chemical elements and their role in shaping the reactions that occur in the high-temperature and explosive events of the cosmos	Cross-section measurements of (i) reactions within the extended CNO cycle, (ii) the competition between (α,p) and (p,γ) reactions along the astrophysical rp-process path, and (iii) reactions between heavy ions at energies relevant to star burning
	Study of the reactions responsible for the p-process nuclei through dedicated techniques such as accelerator mass spectrometry (AMS)
	Measurement of the mass and decay properties of neutron-rich nuclei close to the r-process path, especially around the N=82 rare-earth abundance peak and $N = 126$ waiting points
	Development of the surrogate reaction technique for the determination of reaction yields along the s-, rp-, and r-process paths
3. Understanding the dynamics governing interactions between nuclei at energies in the vicinity of the Coulomb barrier	Study of the hindrance of fusion at extreme sub-barrier energies, especially in systems of relevance for nuclear astrophysics
	Understanding the impact of nuclear structure (deformation, shell structure, diffuseness, dissipation, etc.) on fusion, especially for reactions leading to $Z>100$ nuclei
	Understanding the impact of neutron excess on nuclear reactions in the vicinity of the Coulomb barrier
4. Testing with high accuracy the fundamental symmetries of nature by taking advantage of nuclei with specific properties	Searches for possible extensions of the Standard Model by improving by one order of magnitude or more limits on scalar, tensor, and right-handed components to the electro-weak interaction
	Tests of the conserved vector current hypothesis and the unitarity of the first row of the Cabibbo-Kobayashi-Maskawa matrix from studies of beta decay
	Study of the antineutrino spectra in abundant fission products to determine the origin of the apparent reactor antineutrino anomaly observed in neutrino oscillation experiments
5. Nuclear physics applications at ATLAS and CARIBU	Study via AMS of neutron-capture cross sections on various isotopes of interest for reactor physics and nuclear astrophysics
	Study of the decay properties of neutron-rich isotopes (gamma, beta, beta-delayed neutrons) of importance for accurate modeling of kinetics and decay heat in novel nuclear fuel cycles and for stockpile stewardship
	Studies via heavy-ion bombardment of damage in materials considered for advanced reactors and of modifications to superconducting materials
	Development of new production techniques for specific isotopes for medical and stockpile-stewardship applications

2.2. Research Themes and Goals

The research pursued at ATLAS can be organized into five key research themes. These are to: (i) enhance our understanding of the structure and stability of nuclei as a many-body system of constituent protons and neutrons bound by the strong force; (ii) explore in the laboratory the origin of the chemical elements and their role in shaping the reactions that occur in the high-temperature and explosive events of the cosmos; (iii) understand the dynamics governing interactions between nuclei at energies in the vicinity of the Coulomb barrier; (iv) conduct high accuracy and precision tests of fundamental symmetries of nature, taking advantage of specific properties of nuclei; and (v) execute applied nuclear physics that has broad overlaps with the capabilities of the ATLAS and its CARIBU facilities. The scientific goals that the users devised to best address these questions are given in the table above. While some of these are possible to address with the current capabilities of ATLAS, the majority require new or enhanced capabilities, be it in terms of operations, beams, or instrumentation.

2.3. Program Requirements, Initiatives, and Upgrades

The following is a list of programmatic requirements for ATLAS to meet the challenges set by the users, as taken from the ATLAS Strategic Plan:

- Effective operation of ATLAS
- Increased ATLAS and CARIBU beam intensities and energies
- Increased beamtime availability from the planned ATLAS multi-user upgrade
- Development of unique new radioactive beam capabilities, especially neutron-rich beams, with a reach as far as possible from the valley of stability with the neutron generator upgrade to CARIBU and with the planned $N = 126$ factory
- Development of intense exotic beams of higher energy and purity produced with the in-flight technique at the new RAISOR high-acceptance separator
- Continued effective operation and improvement of Digital Gammasphere and its ancillary equipment
- Targeted campaigns of research with GRETINA/GRETA
- Continued development of the HELIOS spectrometer and its ancillary equipment
- Continued improvement of the FMA and AGFA focal plane instrumentation
- Operation of the AGFA spectrometer for the detection of evaporation residues and products from more complex reactions
- Expanded, dedicated low-background experimental area for low-energy CARIBU experiments and continued development of instrumentation for studies with CARIBU non-accelerated beams

A number of initiatives have been identified to carry out the research program laid forth by the ATLAS user community:

- For the development of a world-class decay spectroscopy program of neutron-rich isotopes, it is necessary to complete the installation of beamlines to the target stations in the new Area 1 hall that will host permanent and visiting experimental setups.
- To increase the maximum beam energy of ATLAS, which is essential for the production of certain in-flight beams, the completion of the 109 MHz cryostat upgrade is necessary.
- For experiments demanding higher intensity stable beams, which are essential for the spectroscopy of high-Z isotopes used in the $N = 126$ factory, and the production of mid-mass in-flight beams, the installation of a new high-intensity ECR ion source is needed.
- For the reliable and predictable production of fission fragment beams from CARIBU, a neutron-generator upgrade is necessary. This comes with the advantage of being able to use different actinides, which have different mass yields. These can be picked to enhance certain programs, such as charged-particle spectroscopy around doubly magic ^{132}Sn.

A multi-user upgrade of ATLAS builds upon the upgrades mentioned above, but also on recently completed updates such as the installation of the EBIS ion source. The time structure of the beam resulting from the charge breeding and release time from the EBIS ion source renders ATLAS empty around 98% of the time. It has been identified that stable beams from the ECR ion source could be injected into ATLAS in the gaps in the time structure, allowing for the acceleration of two beams simultaneously. This has the potential to make available an additional 2000-3000 hours of beam for users and allow for some longer runs (greater than two weeks) to be carried out in a practical manner.

The construction of the $N = 126$ factory is essential to provide access to beams south and east of ^{208}Pb on the chart of nuclides. This is terra incognita. Other radioactive ion beam facilities using fragmentation and isotope-separation-online techniques cannot produce these beams. The technology used here will also allow neutron-rich rare-earth isotopes to be produced. This makes ATLAS capable of answering fundamental questions about the astrophysical *r*-process unlike any other facility.

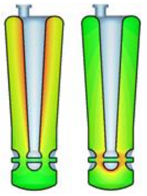
The development of laser spectroscopy capabilities for the new low-energy area has been identified as essential to probe the spin and shapes of neutron-rich nuclei. The chosen approach of collinear laser spectroscopy ideally matches the time structure and energy range of available ion beams in this experimental area and has the future potential to also access isotopes available at the $N = 126$ factory.

Finally, of significant value is the construction and implementation of a new radio-frequency trap for the detection of beta-delayed neutron emission in neutron-rich systems and a new beta-particle spectrometer exploiting cyclotron radiation detection to measure the beta spectrum of neutron-rich systems.

These initiatives and upgrades can be realized over the next 5-10 years at ATLAS and maintain a world-class research program led by the users.

3. Research Groups & Centers

3.1. Accelerator Development



The Accelerator Development group in PHY has unique expertise in superconducting linear accelerators for ions, spanning concept, design, fabrication, commissioning, and operation. The group has extensive practical experience in related areas, such as linear accelerator lattice design, radiofrequency quadrupoles, superconducting magnets, radio frequency power couplers and tuners. The impact of the group's work is seen worldwide with major accelerator hardware and technology operating in ion linear accelerators at the Facility for Rare Isotope Beams (FRIB) at Michigan State University, Inter-University Accelerator Centre (IUAC) in New Delhi, Florida State University, and the Italian Institute of Nuclear Physics (INFN) Legnaro.

Goals:

- Refurbish ATLAS Energy Upgrade cryomodule (Figure 3.1-1).
- Commission the ATLAS Multi-User Upgrade variable energy cryomodule.
- Deliver a Bunch Lengthening System to the Advanced Photon Source (Figure 3.1-3).
- Replace three ATLAS split-ring cryomodules with state-of-the-art modules supporting the ATLAS *N* = 126 factory and super-heavy element program.
- Provide accelerator contributions to the future U.S. Electron-Ion Collider.
- Lead the design and construction of electron and ion accelerators for a dedicated U.S. isotope production facility.

Our core expertise in ion linear accelerators, our strong ties with ATLAS and the DOE Nuclear Physics (NP) Program and national priorities guide our strategy for the next ten years. Primary components of this are: (1) research and development for ATLAS providing unique and scientifically impactful capabilities for ATLAS alongside FRIB and the future U.S. Electron-Ion Collider (EIC), (2) accelerator development for DOE or other accelerator projects that complement or enhance present capabilities, and (3) unique and transformative research to advance the state-of-the-art, especially for ion linacs and, (4) development of new technical infrastructure, new personnel, and U.S. business partners, also focused on ion linear accelerators, to meet the needs of emerging accelerator facilities and applications.

3.1.i. Accelerator R&D for the future of ATLAS

Figure 3.1-1: ATLAS Intensity Upgrade Cryomodule. (Image by Argonne National Laboratory.)

Development plans for ATLAS are phased and aligned with strategic ATLAS priorities to develop a multi-user capability and provide intense stable beams of up to 100 particle microamperes with energies of at least 10 MeV/u over the full mass range. These would support a future ATLAS *N* = 126 factory and a program for super-heavy element production. Presently, the group is refurbishing the last ATLAS cryomodule, the 2009 Energy Upgrade cryomodule, to increase the available accelerating voltage by nearly 50% (14.5 MV to 20 MV) and significantly decrease the ATLAS cryogenic load. Key deliverables are a new superconducting cavity, new high-power RF couplers, amplifiers, and digital controllers. Following this (FY21-24), in support of the ATLAS Multi-User Upgrade, the group is developing a compact superconducting cryomodule to provide independently variable energy beams into a second ATLAS target area. The concept relies on the use of an existing and available quarter-wave resonator, the highest performing such device anywhere, developed recently at Argonne. To facilitate an efficient program that serves multiple users and provides intense beams, the group plans to replace the remaining three split-ring cryomodules. This will be performed using one state-of-the art cryomodule with a timescale for completion of five to ten years.

3.1.ii. Accelerator R&D for other facilities

A powerful complement to the ATLAS developments is the major role of PHY in accelerator research, development, and technology for projects of interest to other branches of the DOE Office of Science. Work performed for DOE High Energy Physics (HEP) and DOE Basic Energy Sciences (BES) greatly enhances the in-house capability to maintain ATLAS at the leading edge of accelerator technology. Key priorities for the accelerator development group over the next five years will be to deliver accelerator systems for the two existing major DOE projects, the Proton Improvement Project II (PIP-II) at Fermilab (Figure 3.1-2) and the Advanced Photon Source Upgrade at Argonne. Both Argonne technologies directly complement the group's long-term goal to provide major contributions to the accelerators required for the future U.S. Electron-Ion Collider (EIC). These contributions involve the concept, design, fabrication and delivery of major components of the electron storage ring and of an electron linac for e-cooling.

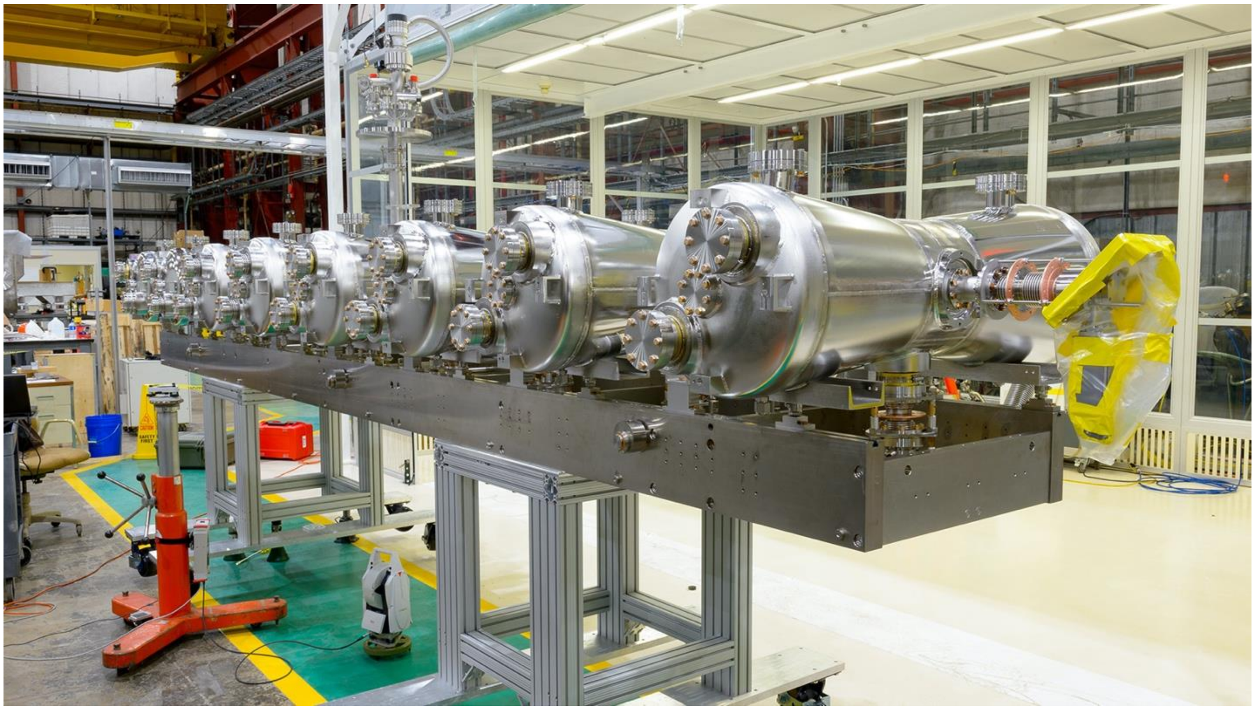


Figure 3.1-2: The half-wave resonator cavities that go inside the Argonne superconducting cryomodule for PIP-II at Fermilab. (Image by Argonne National Laboratory.)

The combination of superconducting accelerator expertise in PHY and the renowned design capability at Argonne's Advanced Photon Source in storage rings provides a compelling opportunity for both the EIC and Argonne. Other compelling 5-10-year opportunities include a U.S. carbon ion therapy facility and the development of a superconducting radiofrequency (SRF) electron injector for application to the Linac Coherent Light Source at the SLAC National Accelerator Laboratory and ultrafast electron diffraction/microscopy.

3.1.iii. Transformative Research and Development

Argonne will continue its decades long leadership to advance the state-of-the-art for ion linacs through innovative developments and targeted research that take advantage of the truly unique capabilities at

Argonne, including its worldwide leadership in low-beta cavity design, fabrication, and processing. In fiscal year 2020, Argonne will begin a program with the aim of transformationally changing the way ion linacs are designed and operated. The vision is for high-performance superconducting RF ion linacs to operate without large, expensive, and complex central helium liquifiers. The opportunity for breakthrough is realistic and stems from the basic physics of RF superconductivity, which strongly favors low frequency cavities needed for ion linacs, from Argonne leadership in low-beta cavities, especially processing, and from recent Argonne developments for the broader accelerator community. The latter have already contributed to large cost savings for other DOE projects.

In fiscal year 2020, Argonne will undertake a program to bring nitrogen doping or lower temperature (120^{o}C -500^{o}C) nitrogen infusion techniques to complete production style low-beta cavities with the goal of major reduction (at least a factor of two but perhaps much more) in RF losses and liquid helium consumption. A factor of two reduction would have an enormous positive impact for ATLAS and other ion linacs, while a factor of three or more would enable operations based on new high-capacity cryocoolers, a true paradigm shift for low-beta superconducting linacs. This new effort will build on critical recent (fiscal years 2018-19) Argonne R&D that has, for the first time, shown us how to efficiently expel trapped magnetic fields in low-beta cavities, a prerequisite to achieving very low losses into helium-cooled cavities. The present plan is to initiate the new effort using an existing full production-style 337 MHz half-wave cavity and to perform nitrogen infusion in collaboration with our partners at Fermilab. The planned Argonne furnace will strongly complement this effort starting in fiscal year 2021. The work is also synergistic with the planned stand-alone cryomodule for the ATLAS multi-user upgrade, which may directly use low-loss cavities resulting from this R&D.

3.1.iv. Accelerator fabrication and testing facilities

The Accelerator Development group has world-leading and unique capability in SRF cavity processing and testing spanning nearly five decades and dating to the inception of the field. Argonne has the only systems and expertise to electropolish cavities for high-intensity ion linear accelerators as required for many of the most promising future accelerator applications. Presently, the joint Argonne/Fermilab Superconducting Cavity Surface Processing Facility at Argonne (Figure 3.1-4) fills processing needs for nearly every current and future DOE accelerator project across the complex, including projects at Michigan State University, SLAC, Brookhaven National Laboratory, Fermilab, and Argonne. A key component of infrastructure, a clean high-vacuum furnace, means that at present 50-100 superconducting cavities/year that are processed at the joint cavity facility must be sent offsite to perform required ultra-clean ultra-high-vacuum (UHV) furnace treatments. The group is working with Argonne partners to bring this capability to Argonne over the next 2 years.

Figure 3.1-3: Bunch Lengthening System cryomodule for the Advanced Photon Source Upgrade. (Image by Argonne National Laboratory.)

To complement the unique Argonne capability to design, build, and process the highest-performing ion linear accelerator cavities, the group plans a major expansion with the goal of building a premier ion linac assembly facility. A promising candidate for this space is a high-quality, existing, but underutilized, 3000 square-foot high-bay located next to the cavity processing facility. The Accelerator Development group aims to transform this space over the next five years into a unique fabrication and assembly area tailored to the substantially different requirements for ion linear accelerators. The facility design will be tailored to requirements for high-power ion linacs such as required for an isotope production facility.

3.1.v. Accelerator development: Long-term planning

Scientific and engineering staff in the Accelerator Development group are supported to a significant extent by sponsored work for others, as well as contributions from Accelerator Improvement Project (AIP) funds. Additional funding supports innovation for future accelerators through funds from DOE R&D, SBIRs, and Laboratory Directed Research and Development (LDRD) projects.

Presently, the group is stretched by technical effort required for ATLAS and other sponsored work projects. This effort detracts from the group's ability to pursue new directions and have a greater impact on new accelerator projects inside and outside of PHY. Furthermore, the group is lacking in a couple of key practical capabilities. We recently performed PIP-II cryomodule assembly in a high-bay space on loan from HEP, and all superconducting cavities are shipped offsite to perform required cavity baking treatments. Staffing and infrastructure plans are intended to address these issues, improving our support for ATLAS and providing greater capabilities to other major DOE projects.

In terms of staffing, near-term expansion of the workforce would be ideal. This includes the hire of a technician and accelerator development specialist to supplement chemistry and cleanroom activities, providing optimal operations for the joint Argonne/Fermilab cavity processing facility. Beyond that, a new cavity fabrication engineer is required to operate the expanded cavity test facility, including support of the refrigerator and purifier operations. Half of the funding should come from the laboratory helium recovery program; half will be divided between NP/LER program funds and sponsored work.

Other investments to support the envisioned program include a new cavity processing furnace (~$1.2M), funded by ANL-IGPE (Institutional General Plant Equipment) and DOE. Operations and maintenance will

Figure 3.1-4: Argonne superconducting cavities being cleaned at the joint Argonne/FNAL Superconducting Cavity Surface Processing Facility (left) and the superconducting cavities being hydrogen degassed in a UHV vacuum furnace (right). (Images by Argonne National Laboratory.)

be covered by sponsored work starting in 2021. Expansion of the Accelerator group's cryomodule assembly capability by transforming a high-bay space into an ion linear accelerator assembly area is planned. Initial funding would be a combination of Argonne, DOE-NP, and sponsored work. Longer term, the replacement of the remaining ATLAS split-ring cryomodules is essential for the effective operation of ATLAS.

3.2. Low Energy Physics

Low-energy nuclear physics concerns itself with the study of atomic nuclei, complex many-body systems that make up our universe, and the reactions which produce them in the cosmos. Some 7000 nuclei are predicted to exist, about 300 of which are stable. At present, we have knowledge, to varying degrees, of approximately 3300 nuclei. The Low Energy Physics group carries out experiments at the ATLAS facility, where we have a world class suite of nuclear instrumentation to facilitate our studies, and at laboratories around the world (Figure 3.2-2). Our interests can be broadly categorized by studies in the fields of nuclear structure, nuclear reactions, nuclear astrophysics, and their overlaps and connections with fundamental interactions.

3.2.i. Nuclear structure

The nucleus is a unique quantum many-body mesoscopic system. It is a laboratory for studies of interactions between constituent protons and neutrons. Because of nucleon-nucleon correlations, nucleons self-organize, and this leads to emergent phenomena such as deformation and halos. Knowledge of nuclear properties is crucial for quantitative description of energy generation and nucleosynthesis in stars.

The Low Energy Physics group strives to characterize nuclei and phenomena that are key for understanding nuclear structure. Part of these efforts are centered around magic nuclei, those which have closed shells of protons and/or neutrons. These form the backbone of the chart of nuclides and have played an essential role in our understanding of nuclear structure. In particular, single-nucleon excitations and their changes with changing numbers of neutrons inform us how shell structure evolves.

Goals:

- Determine key properties of a wide range of transuranic nuclei using the Argonne Gas-Filled Analyzer (Figure 3.2-1).
- Realize the full potential of research with beams delivered by the Argonne In-flight Radioactive Ion-beam Separator.
- Contribute significantly to our understanding of the evolution of single-nucleon excitations in nuclei between masses 10 and 50.
- Build key instrumentation for the Facility for Rare Isotope Beams, such as GRETA and SOLARIS.
- Develop a world-leading super-heavy spectroscopy program.
- Reveal the properties of unexplored nuclei with the *N* = 126.
- Develop high-impact research programs at the Facility for Rare Isotope Beams.

Figure 3.2-1: Gammasphere and the Argonne Gas-Filled Analyzer. (Image by Mark Lopez, Argonne National Laboratory.)

Another active area of research is elucidation of the nature of deformation in nuclei away from these closed shells, which can lead to exotic shapes, such as reflection-asymmetric (octupole) and triaxial types of deformation. Their behavior changes with nuclear spin and excitation energy. We also study weakly bound nuclei, where the proximity of the continuum leads to exotic decay modes such as proton, two-proton, or neutron emission, and other perturbations that go against our understanding of nuclear structure as derived from well-bound nuclear systems. The research conducted by the group touches upon nuclei across the chart of nuclides. Light nuclei, which are a testing ground for *ab-initio* calculations and form a bridge to heavier nuclei, are primarily studied using the HELIcal Orbit Spectrometer (HELIOS), a first-of-its-kind charged particle spectrometer designed for the study of direct reactions in inverse kinematics with outstanding resolution. Radioactive ion beams are used in these studies; to enhance our reach, there have been several accelerator upgrades. These include the completion of the Argonne In-flight Radioactive Ion Separator (RAISOR), which will facilitate direct reactions with intense in-flight radioactive beams, something we plan to exploit in the next 5-10 years.

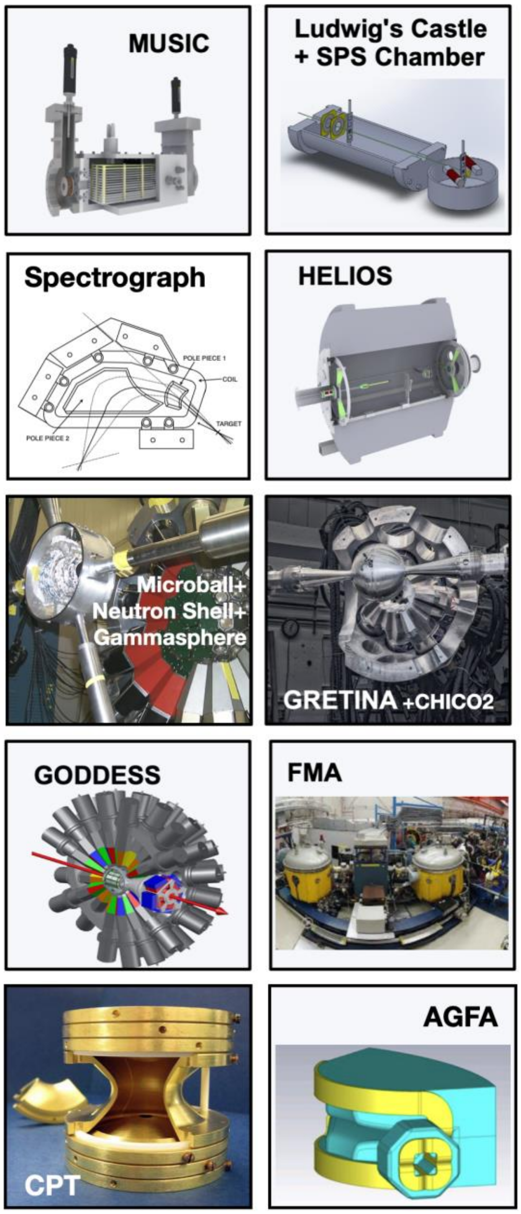


Figure 3.2-2: A sample of the world-class instrumentation used by the Low Energy Physics group at ATLAS and provided by user groups (https://www.anl.gov/phy/instrumentation). (Image by Argonne National Laboratory and Steven Pain, Oak Ridge National Laboratory.)

Nuclei in the proximity of the proton dripline, including doubly magic ^{100}Sn, are currently, and will continue to be, studied with the Fragment Mass Analyzer (FMA) and related instruments. The recently completed Argonne Gas-Filled Analyzer (AGFA) will provide additional opportunities for studies at this frontier. Many experiments utilize the largest γ-ray detector array, Gammasphere, as well as the Gamma-Ray Tracking In-beam Nuclear Array (GRETINA), which is periodically hosted at ATLAS and will continue to be so over the next 5-10 years. Over this timeframe, GRETINA will evolve a more complete solid-angle coverage in the form of the Gamma-Ray Tracking Array (GRETA). Transuranic nuclei and the elusive island of super-heavy nuclei will be studied by using combinations of AGFA and other instrumentation. Beams of ^{252}Cf fission fragments from the Californium Rare Isotope Breeder Upgrade (CARIBU) facility, and the ungraded nuCARIBU facility, will offer access to neutron-rich nuclei, including those around the doubly magic ^{132}Sn, where detailed charged-particle and decay spectroscopy is a primary focus.

The FRIB will offer an exciting opportunity to expand our research towards the limits of isospin, as far as doubly magic ^{60}Ca and ^{78}Ni. To prepare for these experiments the group, in collaboration with other partners, is actively involved in designing and constructing experimental equipment for FRIB, namely, the 4π tracking array GRETA, the solenoidal spectrometer SOLARIS, and the FRIB Decay Station. Concurrently, the complementary research using unique ATLAS capabilities will be continued. The planned $N = 126$ factory will be ideal for studies of neutron-rich nuclei along the $N = 126$ shell closure, which is a key focus of the community, both in terms of nuclear structure and nuclear properties and reactions relevant to the astrophysical rapid neutron capture process. The $N = 126$ factory will provide access to previously unstudied or unobserved nuclei along neutron number 126, potentially close to the path of the hitherto unexplored astrophysical rapid neutron-capture process nuclei. “$N = 126$ factory” is somewhat of a misnomer: changing the targets used for the $N = 126$ factory will also allow neutron-rich rare-earth nuclei to be explored for the first time, as well as detailed decay spectroscopy of nuclei with more neutrons than, e.g., ^{254}Cf and fewer protons.

3.2.ii. Nuclear astrophysics

The purpose of this program is to measure nuclear physics properties such as nuclear reactions rates, β-decays, and masses relevant to different astrophysical processes. The reactions aspect of these studies is carried out with stable or radioactive beams produced in the ATLAS in-flight facility. The program utilizing stopped or trapped CARIBU beams measures properties of neutron-rich nuclides important to the r-process, such as mass, half-life, and β-delayed neutron branching ratio utilizing the Canadian Penning Trap (CPT), Beta-Paul Trap (BPT), or the Scintillator and Tape Using Radioactive Nuclei (SATURN) system.

3.2.ii.a. Studies related to nuclear reactions

The rate of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is one of the most important open questions in nucleosynthesis (Figure 3.2-3). This project, under the leadership of Argonne staff in collaboration with the Fermi National Accelerator Laboratory (Fermilab), Thomas Jefferson National Accelerator Facility (Jefferson Lab), ,and the University of Illinois at Chicago, has been pursuing a technique to study this rate through a measurement of the inverse $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ process using a bremsstrahlung beam from the injector at Jefferson Lab and a continuously operating bubble chamber.

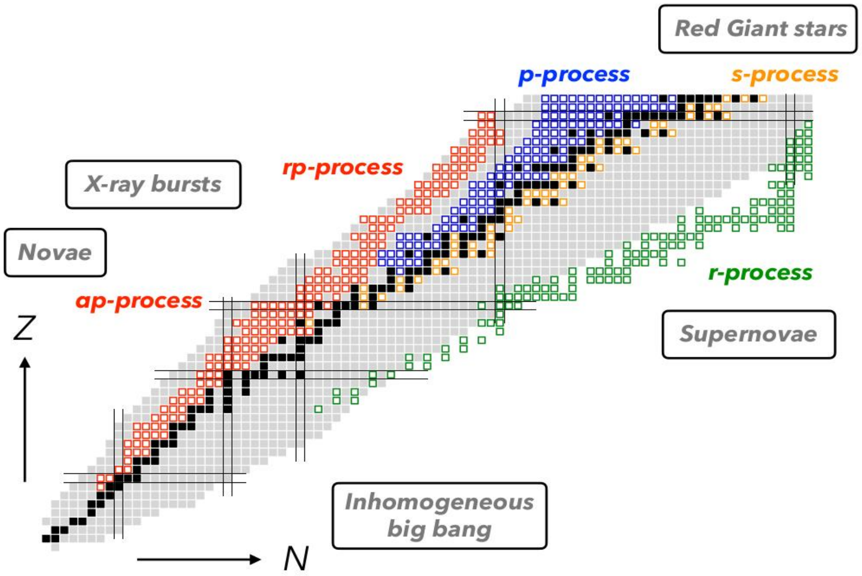


Figure 3.2-3: Nucleosynthesis processes responsible for the generation of the chemical elements. (Image by Argonne National Laboratory.)

3.2.ii.b. Measurement of α-induced reactions

Utilizing both the MUlti-Sampling Ionization Chamber (MUSIC) detector, a simple and highly efficient active target system capable of measuring (α,n) and (α,p) reactions, and RAISOR, important measurements relative to explosive nucleosynthesis will be performed. In addition, (α,n) reactions, which have been demonstrated to have a strong impact on the synthesis of elements in the weak *r*-process happening in neutrino-driven winds in core-collapse supernovae, will be measured with CARIBU beams.

3.2.ii.c. Precision mass measurements

A new “phase imaging” technique to measure masses along with the addition of a multi-reflection time-of-flight system has provided an order of magnitude gain in resolution and improved contaminant suppression for measurement using the CPT. This technique has allowed for the extension of mass measurements to more exotic neutron-rich isotopes at CARIBU. New results have helped pinpoint the astrophysical conditions responsible for the rare-earth *r*-process abundance peak through the use of theoretical calculations, which utilize the high-performance computing capabilities at Argonne. Going forward, a set of measurements is planned to take advantage of the new ^{252}Cf source and the improved CPT. A move of the CPT to the $N = 126$ factory will allow for new mass measurements relevant to the $A = 190$ abundance peaks as well as allow for more precise measurements along the *rp*-process up to $A \sim 100$.

3.2.ii.d. Beta decay measurements using SATURN

While measurements with the CPT provide information on masses and also isomeric states in neutron-rich nuclides, complementary information such as half-lives of isomeric states requires decay spectroscopy. The SATURN instrument, consisting of a tape collection system, Si or plastics detectors to measure β-particles, and Ge clover detectors to measure γ-rays, provides the tools to measure half-lives and decay properties of isomeric states as well as characterize the excited states in daughter nuclides following β-decay. After the relocation of the low-energy CARIBU experimental hall to the old Tandem vault, more neutron-rich nuclides can be studied via decay spectroscopy due to a huge reduction in backgrounds brought about by the proximity of the previous experimental stations to the CARIBU source. Technical upgrades to Gammasphere, which are planned to be implemented in FY21, would allow for Gammasphere to be located in the CARIBU low-energy experimental hall, allowing for more detailed spectroscopy of decay properties of neutron-rich isotopes supplied by CARIBU and, in a few years’ time, the neutron-generator upgrade of CARIBU.

3.2.ii.e. Beta-delayed neutron branching ratio measurements using trapped ions

The β-delayed neutrons emitted from neutron-rich isotopes play important roles in the astrophysical *r* process, the design and operation of nuclear reactors, the structure of neutron-rich nuclei, and the stockpile-stewardship mission. A sensitive technique has been developed using trapped ions to measure neutron branching ratios and energy spectra resulting from β-delayed neutron emission. This technique allows neutron emission to be studied with large and energy-independent detection efficiency, few backgrounds, and good energy resolution. With the construction of a new BPT, these measurements will continue utilizing beams from CARIBU and the neutron generator.

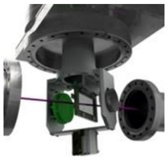
3.2.iii. Challenges, opportunities, and planning in low energy physics

The Low Energy Physics group performs research at ATLAS and other low-energy machines around the world, develops and operates key experimental equipment, and supports the ATLAS experimental program and experimental equipment, including support of outside users. Research is supported by NP-LER funding, while support of the experimental program comes from ATLAS Experimental Support (AES) funds.

Expanded roles of the group are expected both at ATLAS — with the new multi-user upgrade, new capabilities including the $N = 126$ factory, and the expansion into new low-energy beam areas with the addition of multiple beam lines — and in research programs and overlaps with Nuclear Data Program (ND) activities at FRIB. These activities will require additional workforce to be fully implemented. In the immediate future, a request will be made to hire a staff physicist, which would be funded 50% by LER and 50% by ND FY20. The role of this staff member would be to support the experimental program being initiated via ND for targeted experiments as well as perform basic research within the group. With the expanded research program afforded by both the multi-user upgrade and FRIB, we envision adding an additional staff member in FY22 to assist the group in taking advantage of these new physics opportunities. A request will be made to ND to add one additional staff member to PHY to provide increased Evaluated Nuclear Structure Data File (ENSDF) evaluation resources in line with new data capabilities at ATLAS and FRIB and to provide additional support for the world-wide effort in mass table evaluations.

3.3. Low Energy Technical Support

3.3.i. Turning ideas into science



The Low Energy Technical Support (LETS) group provides essential mechanical, electrical, and controls engineering support for all activities relating to the Low Energy Physics group. The LETS group plays a key role in detector development (Figure 3.3-1). The LETS group activities are primarily in support of the experimental program at the ATLAS facility, but also the development and operation of equipment at outside facilities across the low energy community, such as those for FRIB, and for research programs led by PHY at laboratories across the world.

Goals:

- Improve planning, prioritization, and documentation of efforts and costs.
- Track skills and analyze cost/effort data to optimize targeted hires/replacement hires.
- Optimize cost effectiveness and outsourcing.
- Expand the LETS workforce and capabilities of the group to better bridge the gap between the Low Energy Physics group and ATLAS experimental support.
- Balance the groups in terms of skills, high level vs. low level technical support.
- Play an active role in the support of the Low Energy Physics group and broader low energy community in the FRIB era.

Over the last year or so, the organization of the LETS group workflow has undergone a major change, with a focus on planning, prioritization, and documentation of efforts. The goal is to streamline the processing of the ever-increasing workload presented to the LETS group in supporting the ever-expanding capabilities of the ATLAS suite of instrumentation and roles in the low energy community.

With the significantly expanded capabilities of ATLAS and the commensurate increase in new, innovative instrumentation over the last decade, the LETS group faces considerable challenges in aiding the Low Energy Physics group and its support of the ATLAS User Program. The leadership of the LETS group and the documentation and tracking of data with regards to workflow will help the group become more efficient in outsourcing work where appropriate, and in informing future strategic hires as we grow the group as the capabilities of ATLAS grow or replace retired staff.

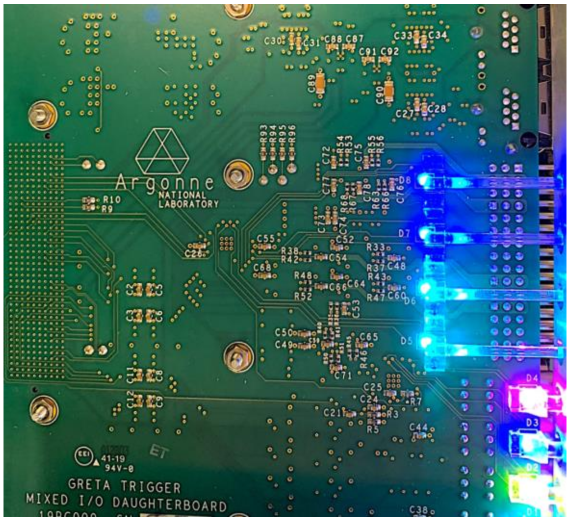
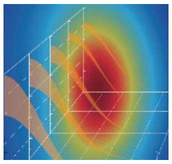


Figure 3.3-1: Image of part of the circuit board for the GRETA trigger module developed by the LETS group. (Image by Argonne National Laboratory.)

In the longer term, our goal is to improve detector support by optimizing the skill sets within the LETS group to better support users in the routine setup and preparations for major experimental instrumentation, with a focus on detector systems. LETS group members focused on detector support will work with the Low Energy Physics group and with the ATLAS User Liaison. This high-level support will be balanced with relevant low-level technicians to help balance the effort of the LETS group.

3.4. Medium Energy Physics



The Medium Energy Physics (MEP) group has a multifaceted program, consisting of three main pillars: the study of hadronic matter in terms of fundamental particles and interactions, the emergence of nuclear structure, and a search for signatures of physics beyond the Standard Model of particle physics. The MEP group has a proven track record of leadership in conceiving and executing novel, high-impact nuclear physics experiments through the development and exploitation of cutting-edge technologies in line with the mission of DOE-NP.

3.4.i. Hadronic physics

The vast majority of visible mass in the universe is a manifestation of the strong force. The strong force binds quarks and gluons together into the protons, neutrons, and nuclei forming the visible matter that surrounds us. We understand the strong force through the theoretical framework of Quantum Chromodynamics (QCD). While the basic tenets of QCD are easily understood, actual calculations are extremely difficult. This is because the strength of the interaction is so high, and the gluon — the carrier of the strong force — couples directly to other gluons, a characteristic unique to QCD. Even today, scientists using the most powerful computers struggle to compute basic properties.

To study the strong force and QCD, the MEP group conducts state-of-the-art experiments at national laboratories, primarily the Jefferson Lab and Fermilab. Additionally, we leverage investments made by other counties in their facilities to further our research goals. Furthermore, we play a leadership role in the science and design of the next generation of experiments, through strategic investments in the Solenoidal Large Intensity Device (SoLID) program at Jefferson Lab and the future polarized high-luminosity EIC facility.

3.4.i.a. Nucleon structure

We have a broad program at Jefferson Lab to study nucleon structure in the valence region. Our group played a leading role in a series of precision experiments comparing electron scattering off tritium (^{3}H) and helium-3 (^{3}He), which is particularly sensitive to small differences between up- and down-quark distributions. Our group designed the novel target system that enabled these experiments. In a next phase, we will study the flavor separation by comparing the proton and neutron form factors measured at high energies.

Highlights

- Leading state-of-the-art experiments at Jefferson Lab, Fermilab, and facilities abroad.
- Search for LHCb charm-pentaquark in photo-production experiment with unprecedented precision.
- Conducting world-leading program to study the emergence of the proton's mass at Jefferson Lab and EIC.
- Towards a first-ever true 3D image of a dense nucleus with the upcoming ALERT program.
- Study short-range correlations in light and heavy nuclei at Jefferson Lab.
- Perform groundbreaking in-house experiment to investigate the matter-antimatter mystery using laser-cooled and trapped radium atoms/molecules.
- Demonstrated first ever high magnetic field performance of superconducting nanowire single-photon detectors.
- Our broad strategic investments ensure continued leadership in the next generation of experiments: EIC, SoLID at Jefferson Lab, neutrinoless double beta decay, QIS, and AI for NP.

Goals

- Understand how the strong force gives rise to the mass, spin, and dynamic structure of protons and neutrons, which make up almost all visible matter in our universe.
- Study the mechanisms and emergent properties of nuclei in terms of their fundamental constituents: quarks and gluons.
- Look for signatures of physics beyond the Standard Model--crucial to explain the existence of our matter-dominated universe.
- Perform critical detector R&D enabling next-generation experiments to operate in harsh, high-luminosity environments.
- Capitalize on Argonne's natural affinity for HPC to develop software for next-generation NP experiments.

We conducted an experiment in Hall C of Jefferson Lab to investigate the validity of charge symmetry in the valence quark distributions through a high-precision measurement of semi-inclusive charged pion production through electron scattering from deuterium. Evidence of charge-symmetry violation in this region, which has never been measured, could have far reaching consequences. Following this endeavor, we can pursue a next generation of charge-symmetry violation experiments by electron scattering from ^{3}H and ^{3}He targets at Jefferson Lab and EIC.

The emergence of the proton and neutron spin through its constituents is one of the fundamental questions in nuclear physics. The quark contribution from the valence region, where a single quark carries a significant fraction of the proton momentum, is still relatively unconstrained. The valence quark dynamics are strongly related to the structure of the QCD ground state itself. We are leading two experiments in Hall C where we scatter electrons from a high-pressure polarized ^{3}He target: one to measure the neutron's quark polarization in the valence region, and one to probe the neutron's color electric and magnetic fields.

Our study of the dynamics of the quarks inside the nucleon spans various endeavors. We are conducting several experiments in Hall B at Jefferson Lab with the CLAS12 detector to measure the transverse momentum distributions of quarks inside the proton, providing access to quantities such as quark orbital angular momentum and quark spin-orbit correlations, with a statistical precision several orders of magnitude higher than the existing state-of-the-art. We will continue this program with SoLID, where we will study the quark dynamics in the neutron, and with an EIC, where we will connect the low-energy to the high-energy regimes, touching on both the quark sea and valence sectors. At the same time, we will explore the universality of these quantities in Drell-Yan scattering from polarized hydrogen and deuterium targets at SpinQuest, the successor the SeaQuest experiment at Fermilab.

Finally, as part of the MUSE collaboration, we will measure the proton's form factor with electrons and muons simultaneously, a high-precision test of the equivalence between electron and muon interactions.

3.4.i.b. Gluonic structure and the emergence of the proton mass

The origin of the proton's mass is a hot topic in nuclear science (Figure 3.4-1), highlighted in the 2015 NSAC Long Range Plan. The emergence of the proton mass within the context of QCD is not yet understood. This mechanism can be studied through quarkonium production near threshold, providing for a novel avenue to study the gluonic structure of nucleons and nuclei, as well as features of the strong force such as the color Van der Waals force.

Jefferson Lab in the 12 GeV era is the ideal laboratory to study *J/ψ* near threshold. The Argonne-led *J/ψ-007* experiment in Hall C will provide for a first high-precision measurement of the threshold area, while also providing a definite answer on the existence of the five-quark resonances discovered by LHCb. Together with the theory group and collaborators worldwide, we strive to develop the necessary theoretical framework to rigorously link experimental observables to the emergence of mass. Looking forward, understanding the emergence of mass in QCD requires a new generation of experiments to study electroproduction of quarkonium, only possible at Jefferson Lab with SoLID and with an EIC, where we can study both *J/ψ* and *Υ* production. Additionally, we can access quantities related to mass generation through pion and kaon Drell-Yan scattering

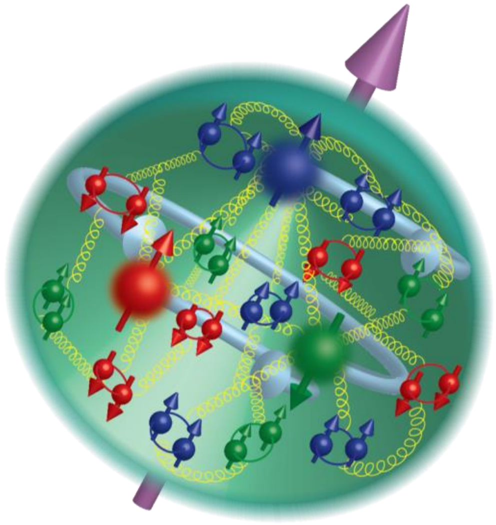


Figure 3.4-1: The proton substructure is an intricate and dynamic system of quarks and gluons. (Image by Argonne National Laboratory.)

experiments. Finally, at EIC we will measure the proton's matter distribution by mapping the gluon distributions in 3D using high-energy quarkonium production.

3.4.ii. QCD in nuclei

Our group leads a cutting-edge program to study nuclei at Jefferson Lab. At the heart of this program lies the description of nuclei in terms of their fundamental constituents, quarks and gluons, and the mechanisms and emergent properties of nuclear physics.

We are heading the Low Energy Recoil Tracker (ALERT) program in Hall B, which aims to measure a 3D image of a dense nuclear system (Figure 3.4-2). We will complement the CLAS12 spectrometer apparatus in Hall B with a specialized low-energy recoil tracker, enabling us to access the low-energy nuclear remnants from an electron scattering off ^{4}He. The experiment will reveal important details on the origin of the EMC effect (how nucleons and quarks are affected when bound inside a tight nuclear system) and advance our understanding of short-range correlations (correlated pairs of high-momentum nucleons generated by the short-range part of the nucleon-nucleon interaction). We will continue this study at EIC, measuring the 3D structure of the quark-antiquark sea of a nucleus.

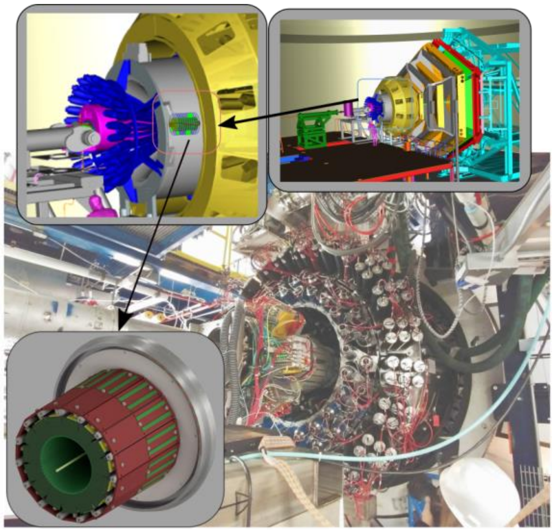


Figure 3.4-2: The low-energy recoil tracker (ALERT), which is a small detector placed inside the CLAS12 spectrometer, will measure the low-energy remnants of nuclear targets. (Images by Argonne National Laboratory and Thomas Jefferson National Accelerator Facility.)

We have led several dedicated studies of short-range correlations, examining their nature in light and heavy nuclei, studying their isospin dependence, and looking for short-range correlated triplets. One of our key findings is that the strength of the short-range correlations is directly related to the modification of the nuclear quark distributions themselves. We will study short-range correlations in Hall A by electron scattering from nucleons of ^{3}H and ^{3}He well above the Fermi momenta, isolating the contributions arising from the hard, short-distance part of the nucleon-nucleon interaction. Looking forward, we have successfully proposed a comprehensive study of light nuclei to examine the impact of clustering and halo structure, as well as a survey of medium and heavy nuclei with a wide range of N/Z ratios to better isolate flavor dependent effects. Additionally, the study of high-energy scattering will allow for a first experimental measurement of the quark structure in a regime dominated by short-range correlations.

3.4.iii. Physics beyond the Standard Model

The third pillar of our program is centered around physics beyond the Standard Model. We are conducting a series of in-house precision measurements of the electric dipole moment of radium-225, and we are strategically investing in a ton-scale search for neutrinoless double-beta decay. We supplement these two main topics with several smaller efforts to look for physics beyond the Standard Model, including a dark-photon search at Fermilab and parity-violation experiments at Jefferson Lab. The search for neutrinoless double-beta decay and the parity violation experiments are conducted under the umbrella of division-wide strategic initiatives, which are discussed in the next chapter of this document.

The fact that the universe is composed primarily of matter rather than being equal parts matter and anti-matter is described by the 2015 NSAC Long Range Plan as "*one of the most compelling mysteries in all of science*." A matter-dominated universe requires significant violation of charge conjugation parity (CP) symmetry, but we have not yet found any sufficiently strong sources. Searches for the electric dipole moment (EDM) of electrons, neutrons, and nuclei are sensitive probes of CP violation. However, no EDM has been observed to date, placing strong limits on the parameter space of beyond-the-standard-model theories.

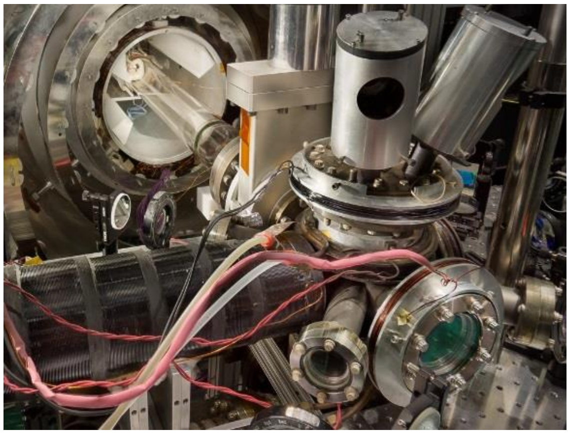


Figure 3.4-3: Our in-house radium EDM apparatus, including the Zeeman slower, magneto-optic trap, and measurement chamber. (Image by Argonne National Laboratory.)

Radium provides for a complementary probe to other ongoing and planned experiments. It is particularly sensitive to CP violation due to its unusual octupole deformation, which enhances radium's would-be EDM by a large factor (hundreds to tens of thousands). The radium EDM experiment at Argonne (Figure 3.4-3) is unique not only in its use of octupole deformations, but also in the technique it uses to measure atomic EDMs. We have for the first time successfully used laser-cooled and trapped atoms to measure an EDM — an achievement that paves the way for future experiments.

Our experiment is far from its systematic limit: we will leverage atomic physics techniques to greatly improve our sensitivity, an upcoming "Blue Light Upgrade" will greatly increase the system's trapping efficiency, and future sources of radium at Los Alamos National Laboratory and FRIB will increase the beam intensity. Through this multifaceted approach, we will reach a sensitivity 10,000 times better than the current state-of-the-art within 5-10 years. To reach even further, we are exploring a novel method using molecules containing radium, which may pave the way for next generation experiments with tremendous sensitivity to CP violation within nuclei.

3.4.iv. Detector R&D and software development

When pushing next-generation experiments and facilities into the luminosity frontier, we have to mitigate challenges due to high detector rates, damaging background radiation, strong magnetic fields, and extreme temperatures, which will spoil a detector's performance. This intensity frontier is the cornerstone of our R&D effort.

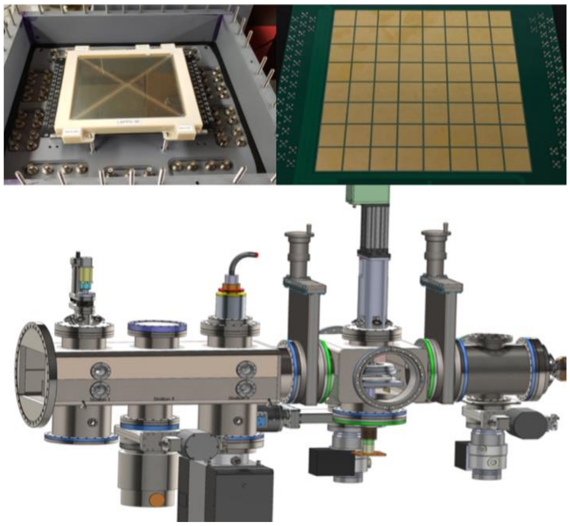


Figure 3.4-4: Top: Gen2 20x20cm LAPPD (left) with Argonne-developed pixelization board (right). Bottom: proposed facility to develop highly-pixelized 10x10cm MCP-PMTs. (Image by Argonne National Laboratory.)

Our group heads the development of next-generation pixelized microchannel-plate photo-multipliers. We are developing an optimized large-area version of this device, in collaboration with Incom, to be used in the at SoLID (Figure 3.4-4). Simultaneously, we aim to build out our unique in-house technology of glass-backed 10x10cm devices, which allow for a very fine-grained pixelization. This technology can play a key role at EIC, neutrinoless double-beta decay and countless other experiments. Our research on superconducting nanowire single photon detectors has found this to be a promising new technology that will transform how we approach near-beamline detection at future particle accelerators such as EIC. Furthermore, we are leading development of a complete simulation and computing toolkit targeting the next generation of high-luminosity experiments at Jefferson Lab and EIC. These efforts are strongly linked to division-wide strategic and emergent initiatives.

3.5. Theory

The Theory group has two core areas of research strength: i) QCD and the quark-gluon structure of matter; and ii) nuclear structure and reactions. The first of these is focused on unraveling how the Standard Model of particle physics gives rise to the characteristics of all forms of strongly interacting matter. This is achieved by developing sophisticated methods in non-perturbative quantum field theory, which are then used to study the properties of nuclear matter and to guide experimental facilities in the United States and worldwide. Emphasis is placed on the science associated with the programs at Jefferson Lab and the forthcoming EIC, such as quark-gluon tomography of nuclei and the associated distributions of mass and spin, quark and gluon hadronization, and QCD effects in nuclei.

The second core strength seeks to understand nuclei and nuclear matter as they emerge from the interactions between their constituent nucleons, the so-called "basic model" of nuclear physics. Realistic two- and three-nucleon interactions and electroweak currents have been developed, as have accurate many-body methods for evaluating them in few- and many-nucleon systems. Within the basic model, we make accurate predictions for a broad range of phenomena, from low-energy nuclear structure and reactions as explored at ATLAS and FRIB, matrix elements for muon capture and neutrinoless double beta decay, neutrino response for oscillation experiments like the Deep Underground Neutrino Experiment (DUNE), and the equation of state for neutron stars, which is ultimately imprinted in the gravitational-wave emission when such stars merge.

The PHY Theory group has a significant impact on a broad array of areas within the gambit of the DOE Office of Nuclear Physics and beyond. In addition, we are developing programs in important emergent fields such as artificial intelligence and quantum information science. These new directions will strengthen and broaden the impact of the Theory group by connecting its expertise to other significant programs in these strategic areas. This provides opportunities for collaboration across the Office of Science and with other divisions at Argonne. As such, these emergent fields provide important growth opportunities for the Theory group, both in terms of staff and resources.

In what follows we describe in more detail the strengths of the Theory group and outline our strategy to increase our impact in nuclear physics and beyond, and to grow the group in funding and staff. This strategy aims to deliver the maximum return on the investment made by the DOE Office of Nuclear Physics and Argonne.

Highlights

- Non-perturbative methods in QCD and hadron structure.
- Mapping the impact of confinement and dynamical chiral symmetry breaking on the properties of matter.
- Comprehensive program to study the tomography of nucleons and nuclei relevant to Jefferson Lab and an EIC.
- Expertise in nuclear quantum Monte Carlo methods and high-performance computing.
- Development of unique low-energy theoretical and computational capabilities related to ATLAS and FRIB physics
- Interdisciplinary research in open quantum systems, high-performance computing, and complex systems

Goals

- Develop leadership in the application of high-performance computing related to QCD.
- Continue to improve *ab-initio* nuclear structure and reactions methods and apply these to neutrino interactions with nuclei and the neutron star equation of state.
- Significantly strengthen the theoretical contribution to the ATLAS and FRIB programs.
- Apply artificial intelligence methods to the science associated with nuclear structure and the EIC.
- Develop a program in quantum information science and its intersection with nuclear physics.

3.5.i. QCD and the quark-gluon structure of matter

QCD is the component of the Standard Model that describes how almost massless quarks and massless gluons interact, and thereby bind together to form the bulk of visible matter in the universe. Quarks and gluons are the fundamental particles of the strong nuclear force. The inner workings of QCD are some of nature's best kept secrets, as never before has science studied a theory whose elementary degrees-of-freedom are not those readily accessible via experiment, that is, whose basic quanta are confined by forces stronger than any previously encountered. QCD has its origins in quantum mechanical models for hadrons and today is the only known example in nature of a fundamental quantum field theory that is innately non-perturbative. QCD describes how quarks and gluons form protons, neutrons, and other hadrons, together with nuclei, and is responsible for creating the vast majority of the mass in the visible universe.

The Theory group has established expertise in non-perturbative modeling of hadron structure and QCD, and leadership in QCD-driven approaches to nuclear structure. To maintain leadership in the forthcoming EIC era, QCD-based methods for nuclei must be expanded and continue to evolve. We will utilize continued laboratory support for the EIC through a strategic initiative LDRD, which provides personnel to continue to develop a solid theory foundation for QCD and nuclei. We will explore partnerships with nearby universities and other divisions within the Laboratory, as well as leverage Argonne's leadership in high-performance computing, to grow the Theory group in numerical computation related to nuclei and the EIC, e.g., lattice QCD. We will strengthen our collaboration with the MEP group and nearby universities to develop EIC-related simulations of observables and detectors, and will work toward establishing a Center of Excellence related to nuclear tomography. This center will use theory input and data to create a tomography of the quarks and gluons in nuclei. We will also develop a strong program in quantum information science, and where possible exploit synergies with the EIC program to maximize funding and impact. The goal is to become the leading theory center for the science of Jefferson Lab and the EIC as it relates to quark and gluon tomography of nuclei and the origin of hadron mass (see Figure 3.5-1 for an example of this research).

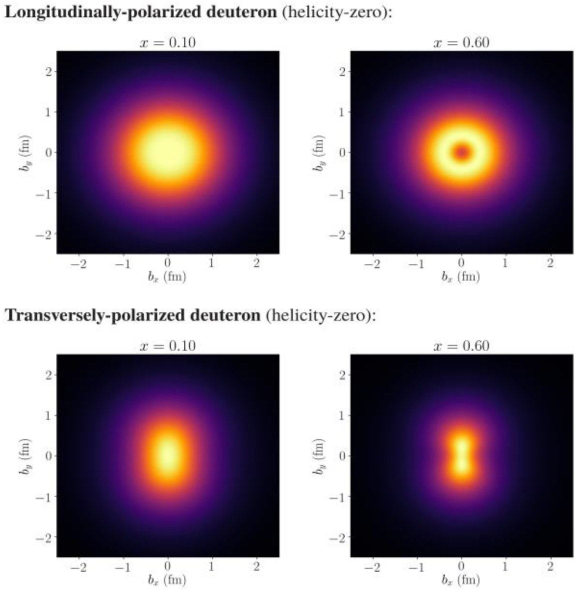


Figure 3.5-1: The deuteron's impact parameter dependent parton distribution function for two deuteron polarization directions and two values for the scaling variable x. (Image by Argonne National Laboratory.)

A foundation for this strategy has already been established. The Theory group is widely recognized for its contributions to the Jefferson Lab program. Important achievements include a prediction for the pion's electromagnetic form factor, which was featured in the Nuclear Science Advisory Committee's 2015 Long Range Plan for Nuclear Physics, and this prediction will be tested at Jefferson Lab. Benchmark contributions have also been made in nucleon elastic and transition form factors, nucleon resonances (e.g., the Roper puzzle), meson and nucleon parton distribution amplitudes, pion and nucleon parton distribution functions, and formal aspects of non-perturbative QCD. Another important component of QCD theory is the study of the quark/gluon structure of nuclei. Key achievements in this area include the development of a field-theoretic framework that provides a natural explanation for the EMC effect and predictions for other QCD phenomena in nuclei, such as quark spin and flavor dependent effects, and the quenching of the Coulomb sum rule, all of which will be tested as part of the Jefferson Lab program.

With a rich program underway at Jefferson Lab and a forthcoming EIC, QCD nuclear physics is at the beginnings of a new era. The Theory group is positioning itself to become the leading center for EIC science as it relates to the quark and gluon tomography of hadrons and nuclei. This research direction stands to make important contributions toward two of the three "high-priority science questions" given in the National Academies of Sciences, Engineering, and Medicine report on the EIC report: *How does the mass of the nucleon arise? How does the spin of the nucleon arise?*

To realize these plans for the Theory group, novel collaboration and growth opportunities must be fostered. With Argonne's leadership in high-performance computing, the Theory group has a strategic advantage with the development of QCD programs that require these resources. The EIC science program brings new opportunities for joint appointments at nearby universities and the prospect for a closer collaboration with programs at Fermilab. A vibrant future for QCD nuclear physics is contingent upon the success of the Jefferson Lab and EIC science programs. It is therefore important that the Theory group fully utilize its strengths and strategic advantages to realize its goal of becoming a leading center for EIC science. These efforts are complemented by partnership with the MEP group and our leadership in Argonne's strategic initiative LDRD in EIC science.

3.5.ii. Nuclear structure and reactions

The Theory group plays a key role in the *ab initio* study of nuclear structure and reactions, starting from the underlying interactions between individual nucleons. We employ nuclear effective field theories (EFTs), which exhibit the symmetries of QCD, to systematically construct realistic nuclear forces and electroweak currents. These are input to our quantum Monte Carlo (QMC) methods to evaluate the structure of nuclei, their transitions, and their interactions with electrons, neutrinos, pions, nucleons, and other nuclei. This is essential for DOE's programs at ATLAS, FRIB, Jefferson Lab, Fermilab, and neutrinoless double beta decay (NLDBD) searches.

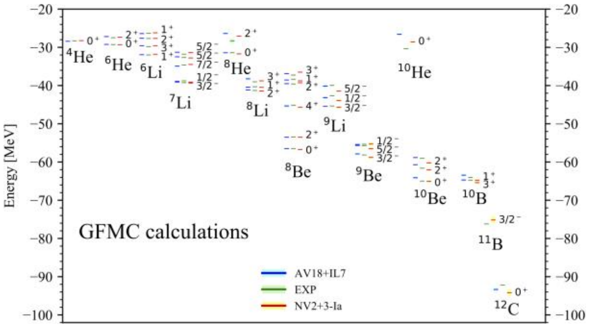


Figure 3.5-2: Energy spectra of A = 4-12 nuclei obtained with the phenomenological AV18+IL7 and Δ-full chiral NV2+3-Ia interactions compared to experimental data. (Image from *Light-nuclei spectra from chiral dynamics*, M. Piarulli *et al.*, Phys. Rev. Lett. 120, 052503 (2018).)

The Green's function Monte Carlo (GFMC) code, which has undergone steady improvement in collaboration with the Mathematics and Computer Science Division and the Argonne Leadership Computing Facility, solves the many-nucleon Schrödinger equation with 1% accuracy for the energies of ground- and low-lying excited states of A≤12 nuclei, and is the most accurate nuclear many-body method available in this regime. GFMC has demonstrated that realistic phenomenological two- and three-nucleon forces, most notably Argonne v18 and Illinois-7, can reproduce experimental energies with high precision (Figure 3.5-2). More recently, an equally good description of the A≤12 spectrum has been achieved with chiral EFT forces that include Δ-isobar intermediate states. Consistent electroweak currents are being used to compute moments and transitions of these nuclei. Alternative QMC methods, including cluster variational Monte Carlo (CVMC) and auxiliary field diffusion Monte Carlo (AFDMC), have recently extended our reach to medium-mass nuclei like ^{16}O and ^{40}Ca, although with lesser accuracy or limited to simpler interactions than GFMC. We are now devising a new "hybrid" QMC algorithm (HQMC), with the goal of GFMC accuracy at much lower computational cost. HQMC will be able to produce the most accurate calculations for nuclei through the carbon and oxygen isotope chains. In this regard, we plan to explore representations of the nuclear many-body wave function based on artificial neural networks. HQMC will help constrain the behavior of the Δ-full chiral interactions for input to the dense β-stable matter equation of state (EoS) for neutron stars, which is already under study with AFDMC. We plan to extend our earlier work incorporating hyperon degrees of freedom in the EoS, making use of both experimental and lattice QCD inputs to construct more accurate hypernuclear potentials.

A major application of our QMC program is the study of neutrinos and weak interactions, including weak decays of light- to medium-mass nuclei, the evaluation of various contributions to NLDBD matrix elements, and predictions of response in neutrino-nucleus scattering to interpret neutrino oscillation experiments. DOE is investing over one billion dollars in these experiments, and the underlying nuclear structure is critical to proper interpretation of the results. GFMC calculations that include two-body currents have been made for the weak decay of A≤12 nuclei, quasi-elastic response for electron and neutral-current neutrino scattering on ^{12}C, and muon-capture rates. The latter are important tools to validate our models of two-body axial current in an energy region that is intermediate between weak decays and oscillation experiments. So far, our calculations have been performed utilizing phenomenological interactions and currents (Figure 3.5-3). To provide robust estimates of the theoretical uncertainty, we will employ the Δ-full chiral Hamiltonians and consistent currents to compute the electroweak responses and muon-capture rates. We plan to utilize deep-learning techniques to improve the accuracy of the response-functions calculations. In the low-energy regime, results will be compared with the COHERENT, LSND, KARMEN, and muon-capture experiments. In the high-energy regime of neutrino-oscillation experiments, we will include relativistic effects and resonance production. This also relates to the short-range correlations observed in (*e,e'pN*) experiments at Jefferson Lab.

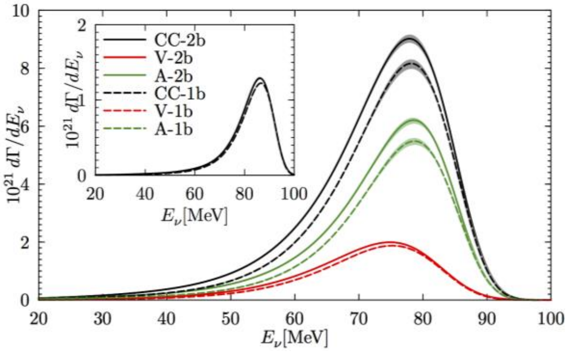


Figure 3.5-3: ^{4}He differential rates obtained with one-body and both one- and two-body terms in the vector (V) and axial (A) components of the charge-changing (CC) weak current, and full CC current, as function of the neutrino energy. The results for ^{3}H are shown in the inset. (Image from *Muon capture in nuclei: An ab initio approach based on Green's function Monte Carlo methods*, A. Lovato *et al*., Phys. Rev. C 100, 035502 (2019).)

3.5.iii. ATLAS and FRIB

Modern nuclear physics is currently laying the foundations for the exploration of the most exotic nuclei ever created. FRIB will reveal thousands of new isotopes (Figure 3.5-4), probing fundamental questions concerning the organization of matter, its properties, and origin. The description of the low-energy properties of those nuclei will require an unprecedented theoretical effort, and the Theory group is playing an important role via the FRIB Theory Fellow Program. This effort aims to predict accurately the limit of nuclear stability, i.e., how many protons and neutrons can form a bound nucleus, or the location of the *r*-process path for the formation of new elements in violent astrophysical processes such as supernovae explosions. These represent some of the major goals of low-energy nuclear physics.

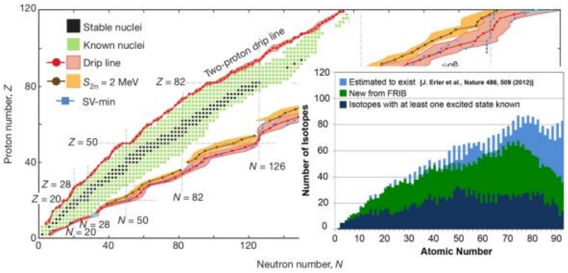
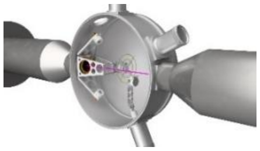


Figure 3.5-4: Projections of how many new isotopes could be discovered, according to density functional theory results, and how much will be discovered at FRIB once operational. (Main image from *The limits of the nuclear landscape*, Erler *et al.*, Nature 486, 509 (2012) and insert image by Brad Sherrill, Michigan State University.)

This effort lies at the intersection of three frontiers of modern science: i) studying open quantum systems, ii) solving the quantum many-body problem using high-performance computing, and iii) understanding how properties of physical systems emerge from first principles. In relation to the ATLAS and FRIB programs, the Theory group is involved in the development of a new effective field theory for the nuclear shell model, allowing precise and systematically improvable predictions of nuclear properties in exotic nuclei, the generalization of the *ab-initio* in-medium similarity renormalization group approach to exotic nuclei, and the computational extension of the density matrix renormalization group approach for high-performance computing.

3.6. Center for Accelerator Target Science

3.6.i. Targets for nuclear science



The Center for Accelerator Target Science (CATS) is the creation of a National Center for Accelerator Target Science based on the existing target development laboratory at Argonne. The most important and primary goal of the CATS is to provide support to the ATLAS scientific program — supplying experimental targets, foils, windows, and radioactive sources and isotopic material for beam production. In addition, the objectives of the center are as follows:

- Serve the low-energy physics community by producing targets when possible or by directing requests to appropriate facilities.
- Train investigators and students in target making to provide a workforce capable of addressing future needs.
- Carry out R&D dedicated to novel production techniques and optimization of existing ones,
- Explore the feasibility of developing an inventory of existing targets that will serve as a pool available to the community.

The CATS is maintaining and continuously developing and improving five facilities within PHY: The Target Fabrication Laboratory (Figure 3.6-1); the Laboratory for Radioactive Materials Handling (the “Hot lab”); the Counting Facility (adjacent to the Hot Lab); a Target R&D Area; and the Target Library and Archives. Information on all these areas, as well as an inventory of targets in the Target Library, can be found at https://www.anl.gov/phy/center-for-accelerator-target-science.

Goals:

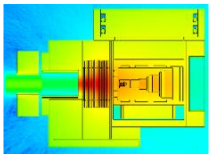
- Carry out the CATS mission in support of ATLAS and the national nuclear physics program.
- Improve infrastructure and increase staffing to maximize operational efficiency.
- Expand into two new research areas: isotope production and nuclear data measurements.
- Develop methods for target reuse and recovery: target inventory to be made available to the low-energy physics community.
- Accommodate the low-energy physics community needs during the FRIB era.

Figure 3.6-1: New evaporator and control terminal in the Target Fabrication Laboratory at CATS. (Image by Mark Lopez, Argonne National Laboratory.)

Currently, the Target Fabrication Laboratory supports target initiatives throughout the nation and is the point of contact for the FRIB Users Target Working Group.

Historically, thin targets have been supplied to the National Superconducting Cyclotron Laboratory, soon to be FRIB, at Michigan State University for their experiments. This demand is beginning to grow with the advent of reaccelerated beam capabilities at said facility and associated experiments. Support also exists for isotope harvesting at FRIB experiments.

3.7. Research with Ion Beams and Isotopes



This group comprises emerging initiatives that extend the research at ATLAS, and the electron linac at the Low Energy Accelerator Facility (LEAF) in the Experimental Operations and Facilities Division, to research and applications beyond basic nuclear physics. Current activities involve research using ion beams for fundamental radiobiology, ion beam therapy, and studies of radiation damage in materials, as well as research and production of isotopes in areas of interest to the DOE Isotope Program. The production of isotopes for distribution to customers through the National Isotope Development Center is exclusively at the LEAF electron linac. The ion beam research is partly hardware development, which does not involve the accelerators except for brief testing of prototypes and use of ATLAS light ions a few days per year. Isotope R&D is directed at high-priority isotopes identified and coordinated through the DOE Isotope Program, mostly using the LEAF electron linac and light ion beams at ATLAS for a few percent of the annual beam hours.

Goals for Isotopes:

- Modify ATLAS target area to enable higher currents for isotope research.
- Develop an ^{211}Rn/^{211}At generator.
- Conduct R&D for Auger-emitting radioisotopes at ATLAS and LEAF.
- Continue production of ^{67}Cu at LEAF.

Goals for Ion Beams:

- Initiate accelerator and beam delivery research for carbon ion therapy.
- Initiate a fundamental cellular radiobiology research program using ion beams at ATLAS.

3.7.i. Isotopes

With cancer incidence rates continuing to climb, research into new and advanced diagnostic and therapeutic radiopharmaceuticals is critical to meeting our nation’s future needs. A growing field within nuclear medicine is personalized medicine tailored to an individual’s unique response. In that regard, a matched diagnostic/therapeutic drug pair allows for low dose imaging and dosimetry estimates followed by a tailored course of therapeutic treatments based on the diagnostic evaluation. The success of this approach is dependent on the high-specific-activity radionuclides.

The isotope program at Argonne is an interdisciplinary program with leadership in the Physical Sciences and Engineering Directorate and research staff in the RIBI Group. There is also strong component of support via scientific and engineering staff and facilities in the Energy and Global Security Directorate. This effort is called the Radioisotope Research and Production Program (R2P2). Argonne is uniquely capable within the DOE to provide high-specific-activity radioisotopes via photonuclear reactions and various light ion reactions inaccessible at other production facilities. LEAF is the only electron linac combined with existing radiological and chemical capabilities in the DOE complex. ATLAS can deliver ions from protons to uranium, which enable unique production pathways. Light ions such as ^{1}H, ^{3}He, ^{7}Li, ^{9}Be, ^{11}B, and ^{12}C can access radioisotopes of interest with high cross sections and low impurity formation, making these reactions ideal for medical isotope development.

Argonne is currently producing ^{67}Cu at LEAF for sale and distribution through the DOE Isotope Program business office, the National Isotope Development Center. This isotope is a theranostic (combined diagnostic/imaging and therapeutic functions) radionuclide being used by several university- and hospital-based groups for pre-clinical tests. Beginning in FY20, ^{67}Cu production will be at the level of one 2-Ci batch per month but can increase with demand to meet rising R&D and pre-clinical needs. R&D is underway or planned for ^{47}Sc, ^{225}Ac, ^{186,189}Re, ^{211}At, ^{188,191}Pt, ^{194}Au, and ^{186}Ir. With this research, Argonne has joined the fight against cancer to provide a better life to all (e.g., Figure 3.7-1).

An important area of research recently initiated is the characterization of Auger-electron emitting isotopes. This research builds on the interdisciplinary collaboration between the isotope research group and the fundamental symmetries group in PHY. To fully utilize the therapeutic power of Auger-electron emitters, it is a high priority to develop an instrumental capability to measure both the energy spectra and multiplicities of the very low-energy electron showers emitted in each decay of an Auger-emitting radio-nucleus. The basis of this instrument development will be the technologies developed by the fundamental symmetries group, namely, the development of very cold atomic beams of radionuclides and very fast timing microchannel detector arrays.

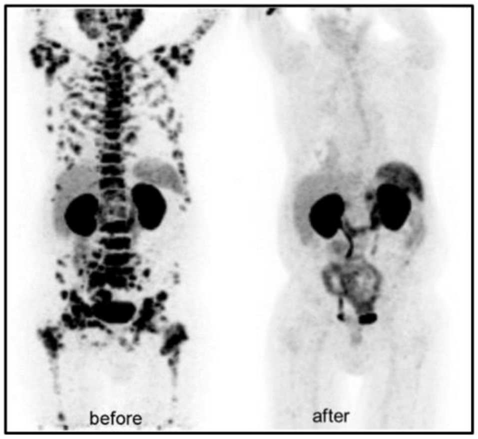


Figure 3.7-1: PET/CT images of patient with extensive metastatic disease before (left, Dec. 2014) and after therapy (right, Sept. 2015) with actinium-225 PSMA-617, showing complete imaging response. The PSA (prostate specific antigen) value dropped from >3000 ng/ml to <0.1 ng/ml. (Image from *^{225}Ac-PSMA-617 for PSMA-Targeted α-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer*, Clemens Kratochwil *et al.*, *J Nucl Med 2016 57:1941-1944.)*

Another important area of development is to advance manufacturing and remote handling of highly activated, irradiated targets and their subsequent processing. This will likely involve robotic retrieval and automated chemical and physical processing, as well as, innovation in hot cell technologies.

We plan to continue and grow R2P2, whose primary purpose is to establish new sources of high-priority radioisotopes for the nuclear medicine community and industry. In the long term, we have the goal of expanding this to a lab-wide dedicated radioisotope R&D and production facility addressing the isotope needs for the medical, environmental, nuclear physics, and national security communities.

3.7.ii. Ion beam therapy

The PHY Accelerator Development group has recently developed a conceptual design for an Advanced Compact Carbon Ion Linac (ACCIL) capable of producing the full energy (450 MeV/u) carbon beam required for cancer therapy in under 50 meters. This development has begun with funding through the DOE SBIR program for one type of high-gradient resonator prototyping, the Argonne LDRD program for the other type of high-gradient resonator prototyping, and the DOE Accelerator Stewardship Program for a compact ion beam scanner that will enable a very compact and lightweight superconducting gantry. This approach has the potential to reduce both the initial and operating cost of facilities for carbon ion beam therapy and, therefore, is worth pursuing as possibly the first such facility in the U.S.

3.7.iii. Fundamental radiobiology

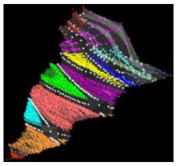
New interdisciplinary research has been initiated to address issues in fundamental radiobiology. One thrust utilizes light ion beams at ATLAS to study the cellular response of normal and cancer cells to direct irradiation with light ion beams. ATLAS light ion beams such as lithium are low energy but have a range of ~2 mm in tissue. Using beams from protons to carbon, a wide range of relative biological effectiveness (RBE) is available. In collaboration with the radiobiology group at Northwestern University Hospital, the development of techniques to use these low-energy, high-RBE ion beams has been initiated with promising results. With the ion beams available at ATLAS, studies of dose-rate dependence over a very large dynamic range are possible to investigate so-called normal and FLASH therapy. In the first study, cells were irradiated to a dose of 5 Gy delivered in 60 msec and 2 minutes, a dynamic range of 2000 in dose rate. This research can provide valuable guidance to the design of full-scale facilities for heavy ion beam therapy.

The other thrust of this research is with therapeutic radioisotopes targeted to deliver high linear-energy-transfer (LET) radiation at the cellular level of cancer tumors. This is an emerging field that uses both

Auger-electron and alpha-emitting radioisotopes. There is a strong synergy between studies of cellular response to high RBE ion beams and high LET radioisotopes. This research addresses the gap between the technology of isotope production and the practical use of these high LET isotopes for cancer therapy. Addressing this gap requires close collaboration between groups with isotope production know-how, radiochemistry and separations know-how, and access to the technologies needed for chelation and bio-vector targeting and tumor cellular targeting. In the Chicago area, the Midwest, and the nation there are many groups of specialists in these required technologies. A goal of this program is to encourage such collaboration beginning with the University of Chicago and Northwestern University. A recently initiated effort is to use radio-*cis*-platin synthesized using Auger-electron-emitting platinum isotopes in PHY and cancer cells grown at Northwestern University Hospital to further study the known synergy between chemotherapy and Auger-emitting isotope therapy.

An important aspect of fundamental radiobiology of high LET radiation is detailed large scale simulations. The RIBI Group will utilize the high-performance computing facilities available at Argonne.

3.8. Nuclear Data



Reliable nuclear structure and reaction data represent the fundamental building blocks of nuclear physics and astrophysics research and have additional outside applications. There is a continuous demand for high-quality updates of the main nuclear physics databases via the prompt compilation and evaluation of the latest experimental and theoretical results. Such credible databases also act as a bridge among science, technology, and society by making the results of basic nuclear physics research available to a broad audience of users, and hence have a profound effect on the socio-economical applications of modern nuclear science.

The DOE-NP funds the U.S. Nuclear Data Program (USNDP), a collaboration of nuclear data experts from national laboratories and academia across the U.S. who compile, evaluate, and disseminate nuclear data for basic nuclear physics and applied nuclear technology research (Figure 3.8-1). The nuclear data infrastructure provided by the USNDP impacts U.S. governmental, educational, commercial, and medical organizations, and it is a part of the U.S. commitment to various international nuclear data networks and collaborations.

The PHY nuclear data program is a key contributor to the USNDP core activities in the areas of nuclear structure and nuclear astrophysics, and their intersections with applied nuclear physics programs. The research activities are distinctive within the USNDP organization, since this is the only group that contributes to the development of the atomic mass tables through the Atomic Mass Evaluation (AME), which has a wide impact on science and applications. In the foreseen

Goals:

- Contribute to the U.S. Nuclear Data Program core activities of compilation & evaluation of nuclear data for the Evaluated Nuclear Structure Data File and the Experimental Unevaluated Nuclear Data List databases.
- Contribute to the development of the new Atomic Mass Evaluation tables.
- Complete experimental activities within the DOE Interagency Nuclear Data Working Group Funding Opportunity Announcement.
- Expand nuclear data research program at ATLAS, FRIB, and other facilities.
- Enhance collaboration with International Atomic Energy Agency.
- Expand the ATLAS nuclear data program to bridge programmatic needs across different DOE offices.

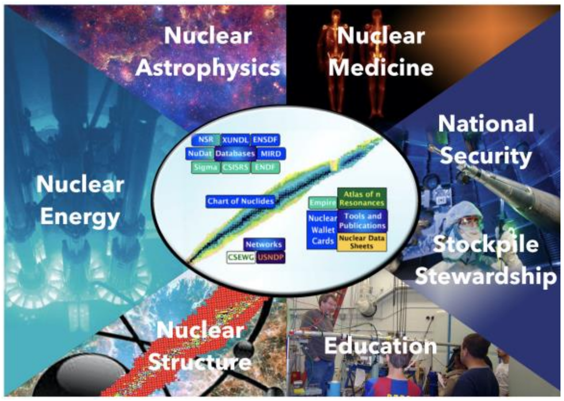


Figure 3.8-1: The core U.S. Nuclear Data Program nuclear physics databases and products and their main areas of impact for science and technology. (Image by Argonne National Laboratory.)

future the program is envisioned to play a leading role in scientific activities relevant to nuclear physics research at ATLAS and FRIB. The unique experimental capabilities at ATLAS will generate nuclear data that are of interest not only to the core DOE-NP mission, but also to programs supported by different offices within the broader DOE complex, thus providing opportunities for a future growth of the program.

The program is already involved in several research projects funded under separate funding opportunity announcements within the DOE Interagency Nuclear Data Working Group that is chaired by DOE-NP. The main thrust is on improving the properties of nuclei in the fission product region by utilizing high-purity CARIBU beams in conjunction with the unique detector capabilities available at ATLAS. Future relevance to research of interest to national security is based on upgrades of CARIBU with a neutron generator that will provide even wider access to further neutron-induced fission products.

3.9. TRACER Center

PHY has strong expertise in neutral atom trapping using laser cooling techniques. We have specialized in using these techniques on atoms of radioactive isotopes to answer select questions in nuclear physics and beyond. Laser cooling techniques are ideal for measurements requiring extremely high sensitivity, selectivity, and precision. Based on this expertise, we have developed the atom trap trace analysis (ATTA) technique for detection of noble gas radioisotopes reaching isotopic abundance sensitivity of better than parts-per-quadrillion. ATTA is an efficient and highly selective laser-based atom counting method, where neutral atoms of the desired isotope are captured by laser light and can be detected one-by-one via laser-induced fluorescence. ATTA is unique among isotopic trace analysis techniques as it is free of interferences from any other isotopes, isobars, and atomic or molecular species. ATTA is now routinely applied to detect the two extremely rare and long-lived isotopes, ^{85}Kr ($t_{1/2}$ = 10 years) and ^{81}Kr (230,000 years), in environmental samples of groundwater and ice to determine mean residence times in the range from ten to one million years. These data are key in applications such as understanding underground water transport for sustainable resource management or reconstructing past precipitation patterns for paleoclimate studies.

Highlights

- PHY developed Atom Trap Trace Analysis (ATTA) as unique tool for noble gas radioisotope detection.
- Radio-krypton analysis in PHY offers wide applications in the Earth sciences and beyond.
- Provides routine radio-krypton analysis of environmental samples.

Goals

- Advancing ATTA technology towards higher sensitivity and sample throughput through targeted R&D.
- Expanding TRACER user base through applications of the ATTA technology into new fields and for new elements.

Figure 3.9-1: TRACER Center laboratory space with third-generation ATTA instrumentation. (Image by Mark Lopez, Argonne National Laboratory.)

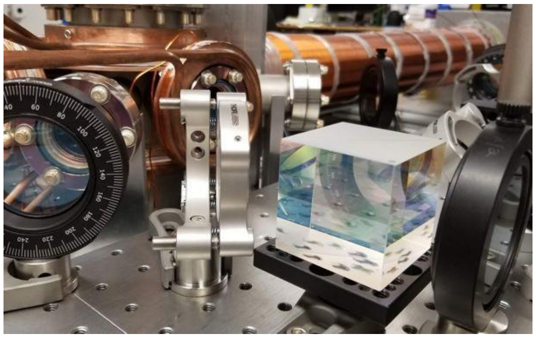


Figure 3.9-2: Optical components in the new TRACER ATTA instrument. (Image by Mark Lopez, Argonne National Laboratory.)

Based on the ATTA technology, we have established the Argonne Trace Radioisotope Analysis (TRACER) Center. It enables broad application of ATTA to the Earth science community and beyond (Figures 3.9-1 and 3-9-2). TRACER now offers a new, third-generation ATTA instrument, gas separation and purification infrastructure, as well as gas extraction equipment to enable easy sampling of water wells for users. TRACER provides routine radio-krypton analysis of environmental samples and strives to further develop the underlying technologies with targeted R&D efforts — in particular, towards a next-generation ATTA instrument that promises to significantly increase sample throughput and sensitivity. This so-called "4th generation" ATTA instrumentation would reach sensitivity and selectivity well beyond any other existing technology. At the same time, we are aiming to expand the ATTA technique to other noble gas radioisotopes such as ^{39}Ar ($t_{1/2}$ = 269 years) with significant applications in oceanography, hydrology, and climate science.

4. Strategic Initiatives

4.1. Electron-Ion Collider

Highlights

- Conducting multifaceted effort: theory, detector R&D, accelerator R&D, and simulation and software development.
- Developing TOPSiDE concept, which leverages state-of-the-art detector technologies while emphasizing simplicity and elegance for an effective central detector subsystem.
- Covariant calculations of key imaging observables to allow unambiguous connections to mass, spin, and force.

Goals

- Elucidate the role of gluons in nucleons and light nuclei via calculations of key imaging observables.
- Conduct simulation-driven optimization of EIC detector concepts through a closed-loop simulation-reconstruction framework.
- Provide essential detector R&D on the LAPPD and ultra-fast silicon technology required for successful EIC detectors.
- Develop robust polarized heavy-ion source using hybrid spin-exchange optical pumping process.
- Perform critical accelerator R&D projects.

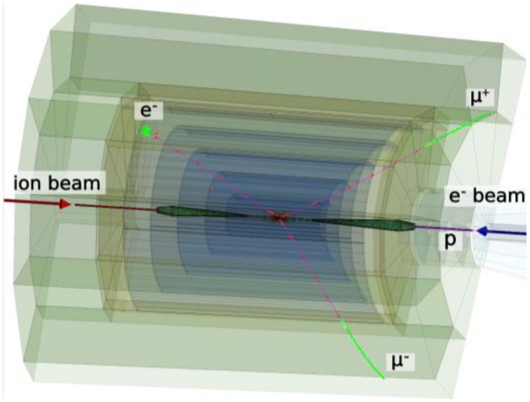


Figure 4.1-1: TOPSiDE concept detector simulation showing an exclusive J/ψ production event. The central detector is able to identify the scattered election and decay muons using time-of-flight. (Image by Argonne National Laboratory.)

The Electron-Ion Collider (EIC) is regarded as the highest priority for new construction in the U.S. Nuclear Physics Program. The planned facility enjoys strong support from the nuclear physics community and recently underwent an in-depth review by the National Academies of Sciences, Engineering, and Medicine (NAS), resulting in a unanimous and strong endorsement of its physics potential and mission need. Argonne is strongly invested in EIC development, with contributions to accelerator R&D and design, theoretical calculations of observables, detector design and simulation, and targeted instrumentation and detector R&D.

The theory effort is focused on understanding how the mass and spin of nucleons arise through non-perturbative calculations of quark and gluon structure. These calculations also focus on unambiguous connections to key imaging observables that can be measured at an EIC for proton and light-ion targets. Predictions for these observables will be used to develop new event generators for physics and detector simulations.

With advances in detector technologies and leveraging expertise, Argonne is developing a novel central detector concept: Timing Optimized Particle-ID Silicon DEtector, (TOPSiDE). Applying state-of-the-art detector technologies while striving for simplicity and elegance, the TOPSiDE concept minimizes the number of central detector subsystems. The strategy of this design isolates the forward regions where instrumentation is the most demanding. Argonne has multiple R&D efforts focused on the detectors needed in these regions, which include ultrafast silicon detectors, large-area picosecond photon detectors (LAPPDs), and high granularity tracking detectors for the extreme forward region. Figure 4.1-1 visualizes a simulation event in TOPSiDE demonstrating the central/forward separation. The scattered electron and decay muons are centrally detected while the recoil protons will be detected in the forward detectors.

Argonne is leading development of a complete simulation and computing tool kit targeting long-term needs of the EIC. The kit includes the generation of physics events, the transportation of particles through the detectors, the digitization of the detector response, the track finding and fitting, and the particle identification. Additionally, we are leveraging the high-performance computing resources available at Argonne to pioneer data processing and movement workflows.

4.2. Facility for Rare Isotope Beams

The Facility for Rare Isotope Beams (FRIB) located at Michigan State University is a new $765M DOE-funded accelerator facility for state-of-the-art nuclear research into the nature of the atomic nucleus. Researchers in PHY are actively involved in, and plan to continue to play a significant role in, the development of novel experimental equipment at the FRIB, including GRETA (Figure 4.2-1), SOLARIS, and the Decay Station (Figure 4.2-2), discussed below. These activities will couple to strong leadership of research programs at FRIB in the fields of nuclear structure, reactions, astrophysics, instrumentation, and targets.

Goals:

- Develop a high-impact research program at FRIB.
- Contribute to the development of GRETA and its future exploitation at FRIB and ATLAS.
- Lead, develop, and build the SOLARIS spectrometer.
- Play a leading role in the development of the FRIB decay station.

4.2.i. GRETA

GRETA is a state-of-the-art, high-resolution, gamma-ray tracking array designed to reveal new insights into nuclear matter. It is being developed by many groups across the Low Energy Physics Community. PHY, through its Low Energy Physics and Technical Support groups, is responsible for the development of the timing and triggering systems, critical parts of the digital data acquisition system for GRETA. (For more information see greta.lbl.gov.) GRETA will also operate at the ATLAS facility in campaign mode.

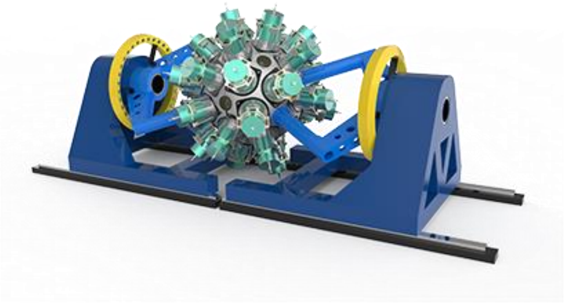


Figure 4.2-1: Artistic rendering of the Gamma-Ray Tracking Array, GRETA. (Image by Lawrence Berkeley National Laboratory.)

4.2.ii. SOLARIS

SOLARIS is a dual-mode charged-particle solenoidal spectrometer designed for the study of nuclear reactions with ion beams of all masses, energies, and intensities of as low as a few hundred ions per second with reaccelerated beams at FRIB. Members of PHY lead this project. At its core is a large-bore superconducting (4 tesla) solenoid, recently tested at Argonne. The goal is to have SOLARIS ready for the start of FRIB operations in 2022.

4.2.iii. FRIB Decay Station

The FRIB Decay Station will be the ultimate tool for decay spectroscopy at FRIB, providing insight into the decay properties of the most exotic nuclei. It is designed to be a highly efficient, granular, modular multi-detector system assembled under a common infrastructure. It builds upon techniques developed at major laboratories around the world over the last few decades. Members of PHY play a leading role in this project, expected to come into fruition in stages, starting early in the FRIB era.

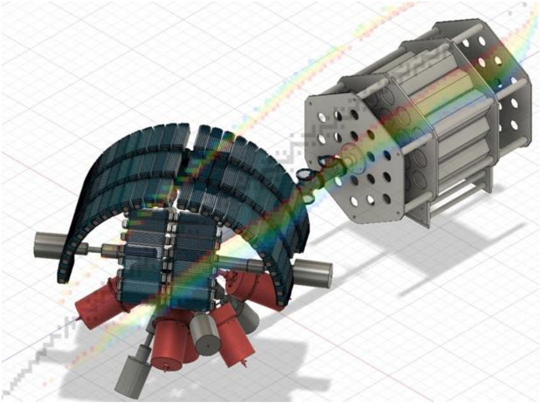


Figure 4.2-2: Artistic rendering of the FRIB Decay Station. (Image by Oak Ridge National Laboratory.)

4.3. High-Performance Computing

The Physics Division has heavily benefited from the Argonne high-performance computing (HPC) capabilities. We are significant users of Mira and Theta — the Argonne Leadership Computing Facility (ALCF) 10-petaflop machines — and we are ready to capitalize on Aurora, the world's first exascale computer, to be deployed at Argonne in 2021.

HPC - enabled capabilities

- Real-time processing at scale for ATLAS and Jefferson Lab.
- ATLAS beamline auto-tuning with machine learning.
- Closed-loop simulations for the EIC design and optimization.
- Performant AI algorithms for 0νββ searches.
- Exascale *ab-initio* nuclear structure and reactions calculations.
- Neural-networks representations of the nuclear wave function.

4.3.i. Low energy at ATLAS

4.3.i.a. Real-time processing of digitized data from ATLAS

A major upgrade of the data-taking capabilities has recently occurred for most of the experimental equipment affiliated with the ATLAS facility. Consequently, far larger amounts of complex data are produced than our local computational infrastructure is accustomed to handling. Post-processing of complete datasets is typically only applied at the completion of an experiment, and unnecessary risks are still in-play, as large fractions of the data are acquired "blindly." We plan to establish a dataflow that can push raw data, process data at scale, and return post-processed data in a real-time (minutes) sense. Work is underway with Globus experts to assist in the data transport. Following the establishment of this pipeline, we will work with experts to optimize and scale our code, while also incorporating artificial intelligence (AI) techniques. It is envisioned that a thousand-fold increase in data evaluation speed is possible, mitigating a major experimental risk and allowing the upgraded digital systems to perform at peak potential.

4.3.i.b. Beamline auto-tuning and monitor system

At present, more than one day per week is spent re-configuring ATLAS when switching between heavy-ion beam species, as no real-time diagnosis for ion beams is in place. A plan has been formulated to develop an automated beam tuning monitoring system, based on deep reinforcement learning (DRL) techniques and a direct feedback loop between beam-ion detectors and optical components. The multiple phases of the project include: sensor construction, data collection, DRL implementation, automation, and continued evaluation. Our ultimate goal is to improve the transmission and quality of the ion beams, while also greatly reducing operation time and effort in beamline tuning. The metric for success is tangible and will be shown through the impact on the science program at ATLAS, with additional available experimental hours and improved heavy-ion beam quality. This technique will require large computational support as hundreds of optical elements and nearly as many sensors will be generated during the 24-hour, 7-days a week operation.

4.3.ii. Medium energy

4.3.ii.a. Reconstruction and analysis of high-luminosity data from Jefferson Lab

The data volumes associated with the new generation of high-luminosity experiments at Jefferson Lab are unprecedented in the field of nuclear physics. The standard approach of exclusively onsite data-processing in "computer farms" is no longer viable. We leverage Globus and Petrel (data management and sharing service) to move data for Argonne-led experiments and allow for data processing using the HPC systems hosted at the Laboratory Computing Resource Center (LCRC) and ALCF. We are investigating an automatized version of this workflow using Parsl (a parallel scripting library for python), in preparation for the CLAS12 ALERT experiments that will push the data volume envelope even further. Our endeavor has synergies with the efforts from the Low-Energy Physics group towards real-time processing of ATLAS and will be particularly relevant for FRIB.

4.3.ii.b. Simulation-driven design and optimization of EIC

Figure 4.3-1: Theta, a 11.69 petaflops system hosted at Argonne National Laboratory. (Image by Argonne National Laboratory.)

The EIC will be the ultimate tool to elucidate the gluonic structure of nucleons and nuclei. There is a strong need for closed-loop simulations to steer its detector R&D and design, ensuring the final machine will be able to deliver the physics goals. Optimizing the detector and machine parameters by repeatedly going through a chain of event generation of key physics processes, followed by detailed detector simulations, digitization, and realistic reconstruction and extraction of the observables, is computationally expensive. We will approach this problem by leveraging the considerable computational resources at Argonne, e.g., Theta (Figure 4.3-1). This provides a pathway to develop a new generation of software for the EIC, e.g., we aim to accelerate the simulation process at scale using generative networks that can fully leverage the capabilities of future exascale machines such as Aurora and Frontier. Similarly, the reconstruction algorithms and data analysis routines can be accelerated by AI-based methods.

4.3.ii.c. Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$) searches are a fundamental part of the experimental program to unlock the secrets of our Universe. Emerging technologies such as high-pressure xenon time-projection chambers offer fantastic 3D resolution of events combined with precision energy resolution. At Argonne, we have been pioneering performant AI algorithms for $0\nu\beta\beta$ searches. We have developed sparse convolutional neural network techniques that exceeded classical state-of-the-art algorithms in accuracy in just 20 min on the Summit supercomputer. We are continuing to extend our AI-based reconstruction algorithms to leverage future HPC resources, such as Aurora. Current demonstrator-level technologies for $0\nu\beta\beta$ are small scale, but NEXT-100 and eventually NEXT-1t will require supercomputer-scale resources for the simulation, storage, and reconstruction of data, not to mention the advantages we can gain from further incorporating AI into our simulation and low-level reconstruction for NEXT. The Medium Energy Physics group’s emerging $0\nu\beta\beta$ initiative will continue to push the state of the art in HPC and AI for $0\nu\beta\beta$.

4.3.iii. Theory

Advances in HPC have been the springboard to first-principle calculations of light- to heavy-mass nuclei and the equation of state of dense nucleonic matter, as found in the interior of neutron stars. The PHY theory group has world-leading expertise in the nuclear Green’s Function Monte Carlo (GFMC) method that allow us to solve the nuclear many-body Schrödinger equation with 1% accuracy. The strong spin-isospin dependence of realistic nuclear forces makes the complexity of the problem scale exponentially with the number of nucleons. To tackle it, over the last two decades we have steadily developed our GFMC code — which relies upon specifically designed asynchronus dynamic load balancing and distributed memory libraries — to take advantage of each new generation of leadership-class computational facilities. We have been participants in the Universal Nuclear Energy Density Functional (UNEDF) and Nuclear Computational Low-Energy Initiative (NUCLEI) as part of the Scientific Discovery through Advanced Computing (SciDAC) programs since 2006, and we have been awarded computing time through the Innovative and Novel Computational Impact on Theory and Experiment and the ASCR Leadership Computing Challenge initiatives, for a total of more than 70-million core-hours per year on Theta and Mira. The reach of the GFMC method will be expanded to larger nuclear systems when exascale supercomputers are deployed. To capitalize on them, we plan to offload the compute intensive loops over the spin and isospin degrees of freedom to GPUs. We will adopt deep-learning techniques — which we already employ to compute lepton-nucleus scattering — to construct sophisticated wave functions for the larger nuclear systems we will treat.

4.4. Neutrinoless Double Beta Decay

Neutrinoless double beta decay (NLDBD) offers a window to new physics. It provides a sensitive probe into the mysteries of the neutrino, including their Dirac or Majorana nature, with implications for unsolved questions in physics, such as the observed excess of matter in the universe. This was highlighted in the 2015 Nuclear Science Advisory Committee Long-Range Plan, which recommended the timely development of a U.S.-led ton-scale experiment.

Neutrinos are point-like fundamental particles similar to electrons, yet they do not have electric charge. These traits would allow them to be Majorana fermions, blurring the distinction between particle and anti-particle and allowing oscillation between matter and anti-matter versions of themselves. The magnitude of the oscillation rate could be linked to the currently unknown absolute mass of neutrinos. Understanding neutrino nature may shed light on their unnaturally light mass and the matter/antimatter asymmetry in the universe.

Argonne is making strategic investments in this area by working with the Neutrino Experiment with Xenon Time Projection Chamber (NEXT) collaboration, which uses pressurized xenon gas for its excellent energy resolution, access to event topology, and continuous purification of fluid source material. Argonne’s xenon work is focused on designing and prototyping key systems for the upcoming 100-kg NEXT-100 experiment (Figure 4.4-1), including the field cage and high-voltage feedthrough, as well as developing a one-of-a-kind local test facility and R&D program for new detector systems suited for high-pressure xenon time projection chambers (TPCs). We will design, develop, and prototype a range of components needed in next-generation pressurized gas xenon experiments. The expertise leveraged in a high voltage, high pressure design will put Argonne at the center of planning and executing a next generation 1-ton-scale experiment in the next decade.

The key advantage of high-pressure xenon TPCs for NLDBD searches is the combination of topological information with precision calorimetry. Techniques for calorimetry are conceptually simple and well established, but Argonne scientists have been leading the development of AI methods for topological selection of events in NLDBD searches. By leveraging supercomputing facilities at Argonne and Oak Ridge, we have achieved state-of-the-art results in mere minutes of AI training, which are scalable to all future xenon TPC detectors. Further development of AI techniques in NLDBD is a key element of our NLDBD program.

Highlights

- The observation of neutrinoless double-beta decay would profoundly impact our understanding of the matter-antimatter mystery.
- Broad and growing collaborations at Argonne, which cross over several divisions and directorates, are being sought.
- High-pressure xenon technology has the potential for a background-free detector, which will allow for ground-breaking ton-scale experiments.

Goals

- Design and build a unique high-pressure xenon time projection chamber to conduct critical R&D on light collection and Ba^{2+} tagging.
- Establish NLDBD group with funding from DOE Fundamental Symmetries Program Office.
- Develop and lead development of AI -based techniques for next-generation neutrinoless double beta decay. experiments.

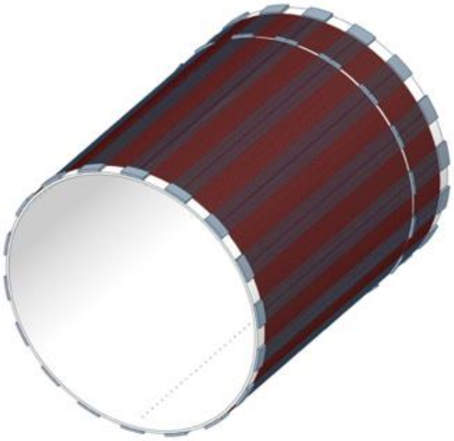


Figure 4.4-1: The Argonne-designed field cage prototype for NEXT-100. (Image by Argonne National Laboratory.)

4.5. The SoLID Experiment

To fully capitalize on the Jefferson Lab 12 GeV upgrade, the proposed SoLID (Solenoidal Large Intensity Device) experiment in Hall A can offer an unprecedented combination of luminosity and acceptance, unlocking access to measurements that cannot be performed anywhere else. Developing this spectrometer (Figure 4.5-1) would entail a confluence of the core competencies of the Medium Energy Physics (MEP) group, which combines leadership of a cutting-edge physics program, detector development for high-luminosity environments, development of software and analysis infrastructure for large-scale electron scattering experiments, and access to world-class engineering resources.

The baseline program of the SoLID experiment consists of three configurations. The first configuration will focus on precision measurements of proton and neutron structure in terms of their internal quark dynamics. In particular, the transverse momentum structure of the neutron will be studied through scattering off a transversely polarized ^{3}He target.

The second configuration will focus on a study of the non-perturbative gluonic structure of the proton through near-threshold J/ψ production. These measurements will shed light on the emergence of the proton mass, constrain the properties of a QCD Van der Waals binding force, and constrain the properties of possible five-quark states discovered by the LHCb experiment.

In its third configuration, SoLID will allow us to study parity, one of the most fundamental properties of nature. In its simplest form, parity conservation means that a process, when viewed in a mirror, should behave the same as it would without the mirror. This seemingly simple property is violated, albeit rarely, by particle interactions involving the weak force. We will use an ultra-precise measurement of parity-violating deep inelastic scattering, measured with the SoLID spectrometer, to test the framework in which we understand the weak force, searching for signatures of physics beyond the Standard Model.

The MEP group is responsible for the design and construction of several critical systems in the SoLID spectrometer. To ensure the high-rate capabilities of the detector and data acquisition system, we conduct targeted pre-R&D measurements through a series of parasitic experiments in Hall C. Furthermore, we provide for leadership in the software development for detector simulations and reconstruction, leveraging Argonne’s capability for high-performance computing.

Highlights

- The unprecedented combination of luminosity and acceptance, made possible with the SoLID apparatus in Hall A, will unlock access to physics processes that cannot be measured anywhere else.
- SoLID pushes the envelope on the readout electronics and data processing capabilities, paving the way towards the Electron-Ion Collider.

Goals

- Perform ultra-precise measurement of the proton and neutron structure in the valence region, disentangling their internal quark and gluon dynamics.
- Understand the origin of the proton mass as a fundamental emergent phenomenon of the strong force.
- Challenge our understanding of the weak force through a precision electron scattering experiment, searching for signatures of physics beyond the Standard Model.
- Leverage the high statistical precision to explore novel ways to study modifications to the proton and neutron structure within a nucleus.

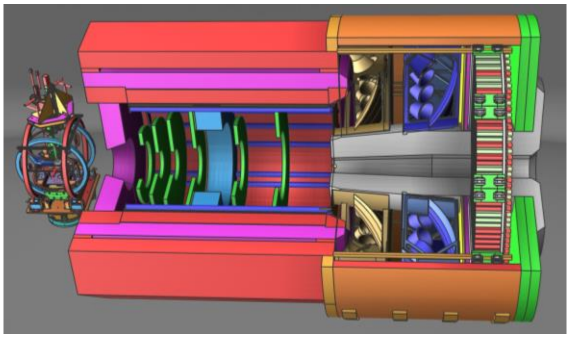


Figure 4.5-1: The SoLID apparatus in its first (semi-inclusive deep inelastic scattering) configuration, with the polarized ^{3}He target on the left. (Image by Thomas Jefferson National Accelerator Facility.)

5. Emergent Initiatives

5.1. Artificial Intelligence

Nuclear physics provides a rich environment with which to develop and utilize machine learning and artificial intelligence (AI) methods. The field is characterized by numerous highly correlated and high-dimension problems that naturally lend themselves to AI. In addition, strong PHY involvement of the Division in several national user facilities, including the operation of ATLAS, provides unique opportunities to develop AI-aware experimental design and implement AI in the construction and operation of detectors and accelerators.

Goals

- Utilize and develop machine learning and artificial intelligence techniques across the research and operational components of the Division.
- Leverage Argonne's significant high-performance resources.
- Leverage Argonne's expertise in AI to develop leadership in AI as it relates to nuclear physics.

The Division has emergent initiatives that utilize AI, including optimizing nuclear structure calculations; performing data analysis and solving the inverse problem associated with the Electron-Ion Collider (EIC); classifying and separating signal from background in nuclear reactions, including NLDBD searches and nuclear astrophysics applications; and using superconducting nanowires to build artificial neural networks.

Machine learning has numerous applications in nuclear theory. For example, the Theory group is using AI to improve *ab initio* nuclear quantum Monte Carlo calculations of neutrino-nucleus scattering. Specifically, deep-learning techniques are employed to retrieve the electroweak response functions from their Euclidean counterparts, a notoriously ill-posed problem. We plan to dramatically improve our current calculations by representing the many-body nuclear wave function in terms of neural-network quantum states.

Understanding the distribution of mass and spin within the proton and nuclei is a key motivation for the EIC (Figure 5.1-1). However, extracting these images is not straightforward and involves the approximate solution to a grand inverse problem. This presents a significant opportunity to employ AI techniques in the analysis of forthcoming Jefferson Lab and EIC data. This is being pursued by the Theory and Medium Energy Physics (MEP) groups. This effort leverages Argonne unique computing resources and is building toward an EIC analysis center at Argonne.

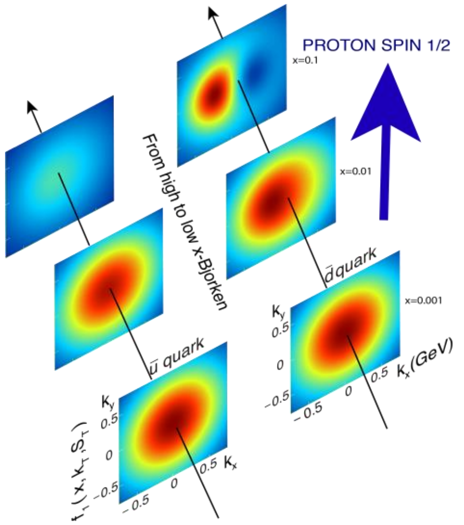


Figure 5.1-1: A momentum space tomography of a hadron at difference slices in Bjorken *x*, for *u* and *d* anti-quarks. The images show how the variable *x* provides a filter to select different aspects of nucleon or nuclear partonic structure. (Image by Argonne National Laboratory.)

Nuclear astrophysics seeks answers to fundamental questions such as: *How all the elements in the universe were created?* The Low Energy Physics group has begun comparing standard analysis methods with AI techniques on existing data relevant to nuclear astrophysical reactions. Standard analysis techniques take months to identify relevant events, and AI methods have the promise to dramatically improve the data analysis timelines. Such methods may significantly accelerate scientific discovery in nuclear astrophysics.

Superconducting electronics are an attractive alternative to normal electronics due to their low power consumption. Recent advances in superconducting quantum sensors, such as superconducting nanowire photon detectors, have found new applications in neuromorphic computing networks, which are a neuro-biological inspired approach to constructing artificial neutral networks for machine learning and AI. The MEP group is pursuing new applications for superconducting nanowire detectors in nuclear physics and is well positioned to contribute to new thrusts of research in AI as they emerge.

5.2. Extreme Materials

Highlights

- Ongoing nuclear material research with ion beam radiation at ATLAS.
- Development and installation of a dedicated material irradiation station at ATLAS (AMIS).
- Conceptual design of a compact heavy-ion linac for the proposed XMAT facility.

Goals

- Installation of XMAT at one of the APS X-ray beamlines.
- Irradiation and online imaging for *in-situ* investigation of material damage that will allow:
    - Fast turnaround of reactor material design and testing as well as benchmarking of simulation tools,
    - Investigation of materials for applications other than nuclear energy, and
    - Potential contributions to manufacturing processes.

Low-energy ion beams can be effectively used to emulate material damage in nuclear energy reactors. Damages that could take years in a reactor environment could, in principle, be reproduced in hours to days by using an ion accelerator. An ongoing experimental program at ATLAS led by a collaboration between the Physics, Materials Science, and Nuclear Engineering Divisions uses fast ion beams for the irradiation of candidate materials. Following irradiation, the materials are analyzed, and their robustness and adequacy for the nuclear reactor environment are evaluated.

In the short term, to take advantage of the ATLAS multi-user upgrade to simultaneously accelerate two ion beams and switch them to different target stations, we will be installing a dedicated irradiation station. It will be located following the first acceleration section of ATLAS, delivering ion beams with energies of 1-1.5 MeV/u.

Longer term, a new extreme material research facility (XMAT) is being considered to enable rapid *in-situ* mesoscale bulk analysis of ion radiation damage in advanced materials and nuclear fuels (Figure 5.2-1). This facility combines a new heavy-ion accelerator with the existing high-energy X-ray analysis capability of the Advanced Photon Source (APS). The heavy-ion accelerator and target complex will enable the emulation of a nuclear reactor environment, making possible the study of fission fragment damage in materials. Scientists will be able to use the measured material parameters to validate computer simulation codes and extrapolate the response of the material in a nuclear reactor environment.

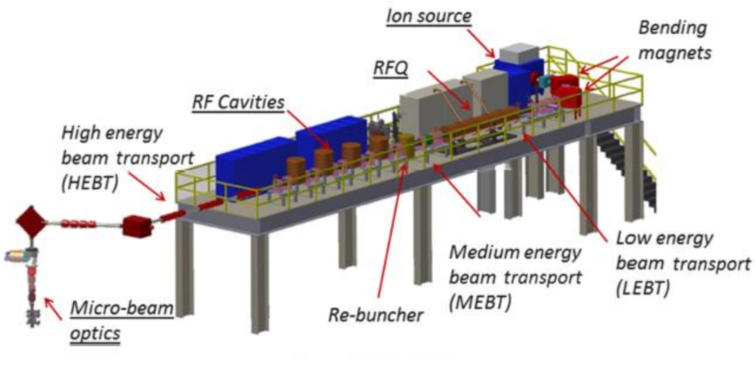


Figure 5.2-1: Concept of the XMAT Linac at the APS positioned above an X-ray beamline. (Image from *Heavy ion linear accelerator for radiation damage studies of materials*, Sergey V. Kutsaev *et al*., Review of Scientific Instruments 88, 033302 (2017).)

The PHY Accelerator Development group has developed a conceptual design for a continuous-wave heavy-ion accelerator capable of providing beams of any stable isotope with adjustable energy up to 1.2 MeV/u for $^{238}U^{50+}$ and 1.7 MeV for protons. The proposed XMAT facility will be unique in the world by offering fast irradiation and *in-situ* imaging of material damage to allow the design and fabrication of more advanced materials for nuclear energy and other applications. Its development will be a multi-disciplinary effort by accelerator physicists, material scientists, and X-ray physicists.

5.3. Ion Beam Therapy

The PHY Accelerator Development group has recently developed a conceptual design for an Advanced Compact Carbon Ion Linac (ACCIL) capable of producing the full-energy (450 MeV/u) carbon beam required for cancer therapy in under 50 meters (Figure 5.3-1). While only synchrotrons are being used in existing carbon ion beam facilities, a linac operated in pulsed mode offers more flexibility in pulse structure, fast pulse-to-pulse energy and intensity modulation, and fast beam switching between ion species. This much desired flexibility in beam tuning enables the fast and efficient beam scanning needed to allow 3D dose painting, as well as real-time image-guided range verification and targeting of moving tumors.

Depending on the tumor shape, size, and location, the required dose could be effectively delivered through a straight horizontal or inclined beamline or through a rotating gantry, with the possibility of beam scanning in both cases. Existing facilities usually have a few treatment rooms with simple beamlines and one room equipped with a gantry system. A room-temperature proton gantry is reasonably sized, but carbon beams require a gigantic gantry due to their larger magnetic rigidity (e.g., the 600-ton gantry recently built at the Heidelberg Ion Beam Therapy Center). In collaboration with the Advanced Magnet Laboratory, we have recently developed a concept for a compact superconducting carbon ion gantry that has the same size but weighs less than the smallest present-day proton gantry.

Highlights

- Development of high-gradient accelerating structure to enable linac-based ion beam therapy.
- R&D for compact superconducting ion beam gantries for 360° beam delivery.
- R&D to combine real-time imaging with ion beam delivery systems for accurate radiation dose delivery.

Goals

- Build a prototype ion therapy linac based on the ACCIL design to demonstrate the technology.
- Establish an advanced ion beam therapy research center that will allow:
  - Comparative studies of different ion beams for cancer therapy,
  - Clinical trials for FDA approval of carbon and other ion therapies,
  - New therapy methods such as FLASH therapy,
  - Cellular radiobiology studies, and
  - R&D for effective imaging methods.

X-ray radiography and cone-beam computed tomography are routinely used to verify that the patient's internal anatomy is positioned correctly relative to the treatment beam. A major limitation, however, is poor soft tissue visualization, which leads to difficulties tracking the target and organs-at-risk motions. Magnetic resonance imaging, positron emission tomography, and ultrasound are potential non-invasive methods that could be combined in real time with a beam delivery system. Developments to combine real-time image guidance with ion beam delivery systems are essential to take full advantage of the physical and radiobiological benefits of ion beam therapy.

Hadron or ion beam therapy research at PHY is aligned along three major axes: the development of high-gradient accelerating structures for the ACCIL linac, R&D for a compact superconducting carbon beam gantry, and the combination of real-time imaging with ion beam delivery systems.

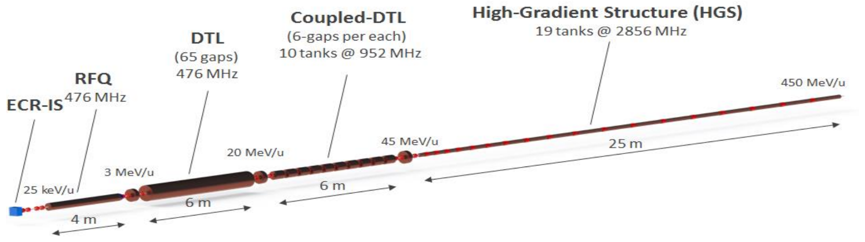


Figure 5.3-1: Schematic layout of the proposed ACCIL design ~ 45 m long. (Image from *Prospects for an Advanced Heavy Ion Therapy Center in the Chicago Area*, B. Mustapha *et al*., AIP Conference Proceedings 2160, 050009 (2019).)

5.4. Quantum Information Science

Quantum computing is on the brink of having a transformational impact on science — and nuclear physics (NP) in particular — because there are vital problems that simply cannot be addressed with existing classical techniques. The significance of these areas of research has been outlined in the National Quantum Initiative, and more specifically, the utility of quantum information science (QIS) for nuclear physics is described in the NSAC report, “Nuclear Physics and Quantum Information Science.” One important application outlined there is the ability to calculate aspects of quantum field theories that have thus far been impossible to solve on a classical computer. Among these are systems at equilibrium with finite baryon chemical potential and time-dependent nonequilibrium processes. Because these QCD observables cannot be calculated with existing classical algorithms, even imprecise solutions would have significant scientific impact. These facts make the quantum computation of quantum field theories a golden application for the quantum devices that are currently under development, and those likely to be available in the near to medium term.

Highlights

- We are developing the tools crucial to simulate and validate basic field theories, leveraging technologies for quantum simulation unique to Argonne.
- Our research on superconducting nanowire detectors has the potential to revolutionize NP and QIS research.
- Groundbreaking research on new quantum sensors will enable the next generation of experiments to search for physics beyond the Standard Model.

Goals

- Demonstrate quantum simulation for field theories in nuclear physics.
- Develop new superconducting detectors and apply them to NP research.

Using our extensive expertise at Argonne, we will build a collaborative program to address these challenges with an analog quantum simulator. By bringing together QCD theorists and experts in field theory simulation and atom trapping, as well as experts in quantum simulation and validation from the Computing, Environment and Life Sciences Directorate, we will have the foundation for a powerful and unique program in this area. Our program will capitalize on solving key challenges which address the noise intrinsic to the devices that will be available within the next decade. Hence, we will favor technologies likely to be quickly scalable.

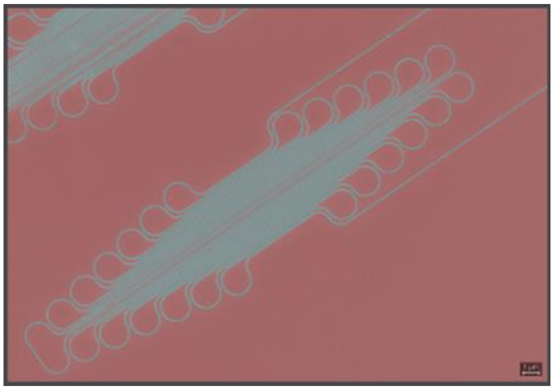


Figure 5.4-1: Prototype superconducting nanowire sensor for use as a highly sensitive photon and particle detector. (Image by Argonne National Laboratory.)

The Physics Division is actively engaged in development of “quantum sensors,” which use quantum principles and have application in both quantum information and nuclear physics. For instance, superconducting nanowire detectors (Figure 5.4-1) potentially have broad applications in nuclear physics. In addition to having excellent position and time resolution, superconducting nanowire detectors offer a unique combination of characteristics which make for an ideal detector for operating in harsh environments. We have developed nanowire detectors that operate in a high magnetic field (>6 T) and with extremely low dark count rate. These devices are important in quantum information on two fronts. First, they are optimally suited to be a single-photon detector for quantum cryptography and computing applications, as detection efficiencies larger than 90% have been achieved. Secondly, nanowires in the form of quantum phase slip junctions are a building block for superconducting digital logic circuits and superconducting qubits. The potential for quantum computers and sensors as applied to nuclear physics is significant and should not be neglected. Argonne is at the forefront of these activities.

6. Diversity and Inclusion

The ideals and practices of diversity and inclusion (D&I) have become a part of the principles that guide the management of the division. This started with the proactive leadership of former Division Directors. During their tenure, they placed a spotlight on the importance of creating a culture of D&I. This initiative began with communicating to and educating staff and leaders in the importance and value of having a diverse workforce and creating and maintaining an environment where all employees have equal opportunity to grow, work, and thrive.

Goals

- Increase communication and training of leaders within the Physics Division to foster a cohesive and inclusive culture.
- Create a rewards and recognition system that highlights the efforts of employees and managers who exemplify support of a diverse and inclusive culture.
- Expand and grow programs and systems that promote diversity and inclusion such that they become part of the fabric of the Division.

Clear messaging related to D&I has been included in recent division meetings, starting with the formulation of monthly all-hands division meetings. It is anticipated this will continue with the arrival of new leadership in the division. In the previous monthly meetings, segments were devoted to sharing an important example or illustration of what D&I looks like, both within and outside of the workplace. There has also been a greater emphasis placed on education of staff and leaders on understanding how unconscious biases impact our decision making in regard to hiring, promoting, and selecting staff for projects, etc. The goal of the division is to provide the tools, education, and systems that will assist all employees and leaders in becoming more aware of their biases in order to establish a more inclusive work environment.

Figure 6.1-1: The Physics Division's approach to diversity and inclusion is aligned with Argonne's Core Values. (Image by Argonne National Laboratory.)

Because of the recent strong leadership provided by the Division Directors in this area, PHY has already begun an evolution in culture and practice regarding the importance of incorporating practices that emphasize D&I. Additionally, the laboratory has hired a Human Resources Manager to support the division and our Associate Laboratory Director, who has a history of managing D&I programs for large organizations. This key hire will provide the division with the specific and practical expertise needed to create and implement a successful D&I strategy for the long term. The division plans to incorporate further the best practices related to D&I that will build a culture of inclusiveness. Our goal is to foster a work environment that allows equal opportunity for all employees. Additionally, the division values a culture where all employees are treated with respect and support without fear of harassment, discrimination, or exclusion. The leaders and managers of the division are committed to continuing to educate their staff as the programs and practices of D&I become further defined, articulated, and communicated in the division. These practices are codified in Argonne's Core Values.

7. Safety, Standards, & Data Management

7.1. Safety, standards, policies

Figure 7.1-1: The Physics Division approach to safety follows lab-wide policies. (Image by Argonne National Laboratory.)

The Physics Division operates under the same general safety guidelines as the broader Laboratory. There have been strategic shifts in how the Laboratory as a whole has approached safety in recent years, building from the Integrated Safety Management to the Improving How We Work initiatives. The division has actively engaged in these initiatives, with representatives on lab-wide committees.

The division has a General Safety Committee populated with a broad range of subject matter experts (SMEs) and, for the ATLAS User Facility, a Radiation Safety Committee, which works closely with Health Physics in assessing ongoing and upcoming experiments with the ATLAS accelerator. These committees provide guidance to the Division Director.

Safety is the division's number one priority. All documentation and policies are frequently reviewed and will continue to be so. With the new AWARE system at Argonne, many dated or paper documents are being revisited as they are reframed in the AWARE system. Over the next several years, there will be an ongoing concerted effort to ensure that "Skill of the Worker" documentation exists for many tasks carried out by groups across the division, and that all paper copies of any work planning and control documents are modernized and available in the AWARE system.

The long-standing ATLAS Radiation Interlock System is due to undergo a complete overhaul over the next few years. This system is critical to the safe operation of the ATLAS facility, where the accelerator and the beams it delivers can be the source of significant prompt radiation. This work, like many nonstandard projects in the division, will be done with lab-wide support from SMEs.

All documentation, policies, and standards specific to PHY can be found via the newly updated website, which also provides direct links to the Laboratory Management System. The division is always looking for ways of improving the safety and training of ATLAS users, too. It does this in cooperation with ATLAS management and its User Liaison. There has been significant improvement over recent years in allowing users to take online training remotely, prior to their visit.

7.2. Data management

Data generated by research groups are maintained in accordance with the guidelines of DOE, which has developed a policy for Digital Research Data Management (https://www.energy.gov/datamanagement/doe-policy-digital-research-data-management). In general, all data are available upon request for some period of time, unless they are deemed sensitive. Several research groups are attempting to make internet-accessible data available to users, including for the monitoring of the status of experimental equipment.

8. Communication Strategy

The communications strategy of the Physics Division is multifaceted and must be effective on many levels. We have a responsibility to communicate our mission, capabilities, and achievements to a broad range of stakeholders, which include the public, our funding agencies, collaborators from other national institutions, directorates and divisions across the laboratory, division staff and, in connection with the ATLAS facility, our broad international user base. This responsibility presents a significant challenge that we are confronting through a strategic communications program.

Goals

- Full implementation of the new Physics Division website, integration with ATLAS and the Lab.
- Move towards routine publication of research highlights, new stories, and other public-facing communications.
- Overhaul internal communications through retreats and rotating posters.
- Implement advanced, interactive, web-based communications with public, users of ATLAS, and other stakeholders.

Central to our communication strategy is the Physics Division website. We have recently implemented the first complete overhaul of the division website in over a decade. The key focus is to bring to the forefront our core capabilities and our scientific achievements, but also provide a detail-rich resource.

The new website is highly visible to the casual browser of the general Argonne website, with our news stories, achievements, highlights, and capabilities readily available from the Argonne home screen when relevant. Longer term plans include streamlining the way in which users of the ATLAS and other Division facilities, such as the Center for Accelerator Target Science and the Trace Radioisotope Analysis Center, interact with PHY personnel, schedules, and so on, through the website.

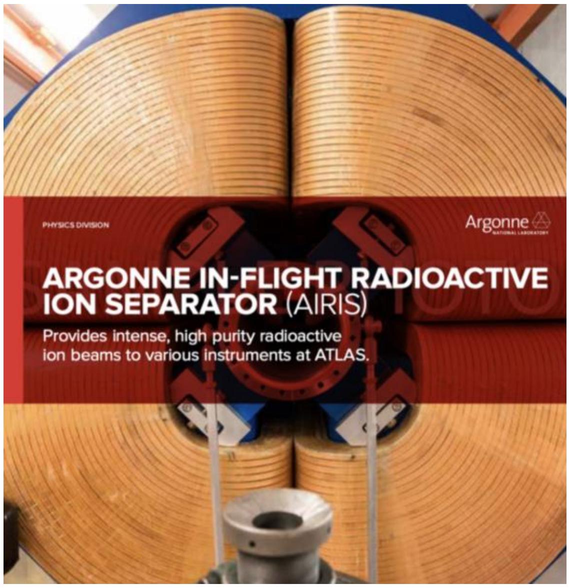


Figure 8.1-1: High-visual-impact poster of one of our new state-of-the-art capabilities, AIRIS. (Image by Mark Lopez, Argonne National Laboratory.)

Internal communications — those to division staff and other Argonne entities, as well as to division visitors — are evolving as well. In connection to ATLAS, plans for a new quarterly newsletter called ISOtopics are well under way. The intent is to bring communications from and about our primary user facility to the community that uses it and also to a wider community through the many mailing lists the newsletter will be pushed to. In addition, the ATLAS facility has recently joined SSURF, the Society for Science at User Research Facilities, broadening its audience. The presentation of our work within the division is changing, with new artwork to line the entrance hallways to the division. Focusing more on the staff in 2018, we had the first division-wide retreat with the aim of fostering communication and awareness across the entire division, which exposes synergistic opportunities not always apparent. Plans to make this an annual activity are being considered.

In summary, our communications strategy is to best inform sponsors, the public, the users, and division personnel of the activities, capabilities, accomplishments, and visions of the division on day-to-day, medium, and long-term timescales.

9. Summary

This strategic plan for FY2020-24 outlines a program that will broaden and strengthen the Physics Division's role as a leading institution for nuclear physics. At its core is the continued operation of the Argonne Tandem Linac Accelerator System (ATLAS), which is the DOE facility for low-energy nuclear physics and one of three national user facilities for nuclear physics, together with Jefferson Lab and the Relativistic Heavy-Ion Collider (RHIC). While ATLAS provides a foundation, the Physics Division's program in nuclear physics is broad and multifaceted.

There are world-leading programs that study the fundamental theory of the strong interaction — Quantum Chromodynamics — both in theory and via experimental programs at, e.g., Fermilab and Jefferson Lab. These programs are now also focusing on the Electron-Ion Collider (EIC), which is the DOE's number one priority for new construction after the completion of Facility for Rare Isotope Beams (FRIB) and the Solenoidal Large Intensity Device (SoLID) experiment at Jefferson Lab. *Ab initio* approaches to nuclear structure were pioneered in the Physics Division and continue to provide benchmark results for the properties of nuclei with $A \leq 12$. Utilizing Argonne's high-performance computing resources, these methods are being extended and adapted to much heavier nuclei and will have increasing impact on the ATLAS and FRIB programs, together with the neutrino program at Fermilab. Significant upgrades are planned for the Atom Trapping Lab that will enable ever tighter experimental limits on the electric dipole moment of radium-225 and physics beyond the Standard Model. A program is being developed in neutrinoless double beta decay that will see the Physics Division play a major role in the Neutrino Experiment with Xenon Time Projection Chamber (NEXT) collaboration and the forthcoming NEXT-100kg experiment.

ATLAS continues to evolve its capabilities to enable users to deliver a world-class research program in low energy nuclear physics. The newly upgraded facility for the in-flight production of radioactive ion beams (RAISOR) and novel instrumentation, such as the gas-filled separator for the Argonne Gas Filled Analyzer, will realize their full potential in the coming years. Neutron-rich fission-fragment beams, allowing access to nuclei produced in explosive nucleosynthesis, are provided by the Californium Rare Isotope Breeder Upgrade (CARIBU), which will be upgraded to allow for neutron-induced fission, substantially expanding the reach of CARIBU. Access to neutron-rich rare-earth nuclei and isotopes with $N > 126$, a unique capability allowing us to explore terra incognita, is planned with the implementation of the $N = 126$ factory at ATLAS. A new low-background experimental area has recently been developed for high-sensitivity decay studies. The Low Energy Physics and Support groups have significant roles and research leadership at laboratories outside of Argonne and in supporting the low energy physics community, for example, through roles in projects, such as the Gamma-Ray Tracking Array and the planned development of new instrumentation for FRIB. The Physics Division's Accelerator Development group has world-leading expertise in superconducting linear accelerator technology, which is leveraged by ATLAS to enhance and upgrade components of the linac to provide higher energy and intensity beams. The group also plans to incorporate their novel technology into other facilities at Argonne, with the upgrade of the Advanced Photon Source, and in facilities around the world.

The Physics Division is beginning to develop programs in emergent areas of broad importance to the DOE Office of Science. This includes research at the intersection of quantum information science (QIS) and nuclear physics, with plans to develop purpose-build tools crucial to the quantum simulation of quantum field theories of direct relevance to nuclear physics. The Physics Division is also engaged in the development of quantum sensors, which could lead to applications in quantum cryptography and quantum computing. Artificial intelligence (AI) methods are also beginning to be used across the Physics Division programs, including nuclear theory, in the analysis of experimental data and in accelerator and detector operation and design. Argonne's leadership in high-performance computing provides unique opportunities to develop cutting-edge programs that utilize AI to drive nuclear physics discovery and maximize return on investment.

The Physics Division has a strong commitment to Argonne’s Core Values: Impact, Safety, Respect, Integrity, and Teamwork. It strives to develop and maintain the highest standards in safety and data management and is continuously exploring new ideas and opportunities to improve diversity and inclusion among its personnel. The Physics Division is also actively engaged in outreach to the broader scientific community and the general public, e.g., through Argonne’s longest running weekly colloquium series, public lectures, and the supervision of high school and undergraduate students via various internship programs.

The implementation of this strategic plan will see the Physics Division broaden and strengthen its leadership in nuclear physics and beyond. It will lead to key roles at the EIC and FRIB and the development of strong programs in QIS and AI. This strategic plan aims to provide maximal return in the investments made by the DOE and by Argonne.