Laboratory for Nuclear Science

The Laboratory for Nuclear Science (LNS) provides support for research by faculty and research staff members in the fields of particle, nuclear, and theoretical plasma physics, as well as quantum information theory. This includes activities at the MIT-Bates Accelerator/Research and Engineering Center (MIT-Bates Center) and the Center for Theoretical Physics (CTP). Almost half of the faculty of the Department of Physics conduct research through LNS. During fiscal year 2016, total research volume using funding provided by the US Department of Energy (DOE), the National Science Foundation (NSF), the Army Research Office, and other sources was $21.3 million, an increase of about $2.1 million from the previous year, and an amount more in line with a 10-year average of $22.2 million. This increase was because of the launch of new research programs by several younger faculty and researchers and the start of construction on several projects. LNS researchers are successfully pursuing multiple funding opportunities that should maintain or even increase research volume in the future. Seven LNS junior faculty hold prestigious Early Career/CAREER Awards from DOE and NSF.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at CERN in Geneva, Switzerland, at the Fermi National Accelerator Laboratory (Fermilab) in Illinois, and at a number of other locations around the globe and in space. The overall objective of current research in high-energy particle physics is to test as precisely as possible the Standard Model of particles and forces, which has been very successful in describing a wide variety of phenomena, and to seek evidence for physics beyond the Standard Model. LNS researchers are deeply involved in much of this research.

LNS researchers are playing a major role in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN, in the areas of data acquisition and distribution systems, detector upgrades, and data analysis. LNS scientists also are leading the program to study high-energy heavy-ion collisions with CMS. The LHC is now running at 13 teraelectron volts, nearly the design collision energy, and is quickly ramping up the luminosity. With the discovery of the Higgs boson accomplished, LNS researchers are using CMS to measure detailed properties of the Higgs boson and also to search for dark matter, using the signature of missing energy in the detectors. Associate Professor Markus Klute has been granted tenure.

The Alpha Magnetic Spectrometer experiment (AMS-02), led by the Electromagnetic Interactions (EMI) Group in LNS, is designed to look for cosmic antimatter and evidence for dark matter by operating a large, 6,717 kg magnetic spectrometer above Earth's atmosphere on the International Space Station (ISS). AMS has been collecting data since 2011; it has now collected more than 80 billion cosmic ray events. The EMI Group leads the data analysis effort. It is also responsible for proper operation of the spectrometer, a critical and difficult effort given the hostile thermal environment of the ISS. Results have been published this year on the helium flux in cosmic rays.

Figure 1 shows a graph of the flux of helium nuclei as a function of rigidity, as detected by AMS. The data follow a smooth curve that increases from 1 to approximately 35 gigavolts (GV), then decreases slightly (in agreement with a single power law) until about 200 GV, after which the flux increases again. An inset in the figure shows a photo of the ISS, with the location of AMS circled in red, and a comparison of the helium with the proton flux. These results show that the helium flux as a function of rigidity (momentum/charge) deviates from a single power law. However, above 45 GV, the proton to helium flux ratio is well described by a single power law. Data will continue to be collected on electrons, positrons, protons, antiprotons, and helium and other nuclei until the end of ISS operations, presently scheduled for 2024. Vladimir Koutsenko has been promoted to principal research engineer.

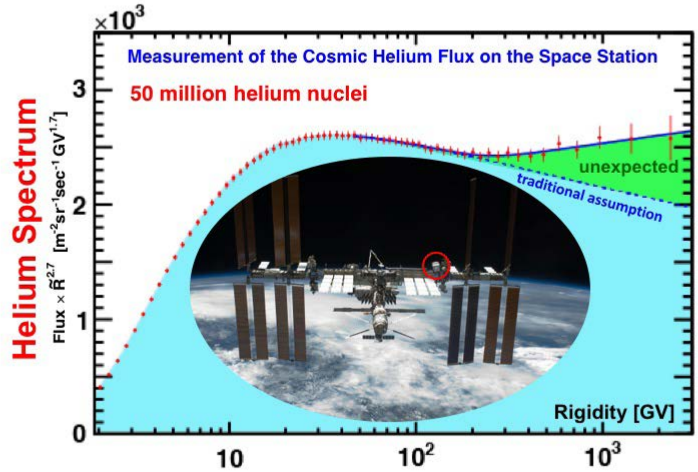

Figure 1: The helium flux in cosmic rays as measured by the AMS on the International Space Station. The inset shows the Space Station with the AMS circled in red.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment (MicroBooNE) and related experiments at Fermilab. The group participates in the IceCube collaboration to search for sterile neutrinos in an experiment at the South Pole. The group also continues to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos, and is in the process of constructing a high-intensity ion source to feed the future synchrotron.

LNS researchers in high-energy and nuclear physics are developing the DarkLight experiment with the help of engineers and technicians at the MIT-Bates Center. The experiment will use the 100 megaelectron volt free electron laser beam at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Virginia to search for a possible light boson that carries a "dark force" through which dark matter is theorized to interact. The Phase I target/vacuum/magnet/detector system will be installed at Jefferson Lab and begin taking data in the summer of 2016.

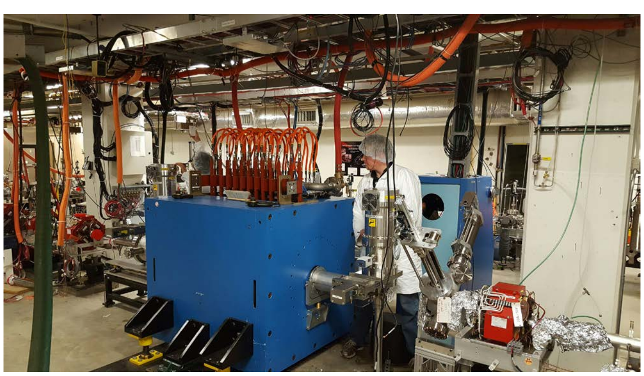

Figure 2: The DarkLight solenoid magnet and vacuum system during installation in the vault of the low-energy recirculator facility at the Jefferson Lab in Virginia.

The DarkLight solenoid magnet is a steel cube approximately 1.25 meters on each side, painted blue. Stainless steel cylindrical beam pipe goes through the center of the magnet, and connects to various beam monitoring devices, vacuum pumps and valves. Orange hoses for water cooling are connected to manifolds on the top of the magnet. The magnet is mounted on a black platform that both supports the magnet and guides it when it is moved out of the beamline so as not to interfere with other experiments.

Experimental Nuclear Physics

At present, experimental nuclear physics has three main thrusts: hadronic physics, heavy-ion physics, and nuclear structure and fundamental properties. LNS has active groups in all of these subfields.

In fundamental properties, LNS nuclear physicists work in neutrino studies, seeking to measure the neutrino's mass and to understand whether the neutrino is its own antiparticle (i.e., a Majorana particle). MIT physicists are part of the Cryogenic Underground Laboratory for Rare Events collaboration at Gran Sasso, Italy, and the Kamioka Liquid Scintillator Antineutrino Detector–Zen collaboration at the Kamioka Observatory, Japan, searching for neutrinoless double beta decay. If such decay is observed, this would imply the neutrino is its own antiparticle. Part of this search involves the development of novel detector techniques, including the use of quantum dots and development of scintillating bolometer detectors.

Figure 3 shows (left) two students working on the inner components of the dilution refrigerator (four horizontal circular platforms about 30 cm across, stacked vertically, with connecting rods, cooling loops, bellows, and small sensors, can be seen); (top) a roughly spherical crystal, about 1 cm in diameter, glowing purple in ultraviolet light; (bottom) five silvery disks of silicon light sensors; and (right) an undergraduate wearing green gloves holding a length of clear fiber with part of the dilution refrigerator in the foreground.

Figure 3: A collage of photos from scintillating bolometer research and development work: (left) a graduate and an undergraduate student install sensors in the dilution refrigerator; (top) crystal test growth of ZnMoO4 at RMD Inc.; (bottom) anti-reflective coatings for silicon light sensors; (right) an undergraduate student installs calibration fiber in the dilution refrigerator.

MIT physicists are also playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment at Karlsruhe, Germany, and in the Project 8 experiment, both of which intend to make a new precise measurement of the mass of the electron neutrino using the endpoint of the electron energy spectrum from tritium beta decay. KATRIN commissioning is under way. Project 8 is developing a novel technique to measure the electron neutrino mass even more precisely than KATRIN, using frequency measurements. Measurements on electrons emitted by a radioactive isotope of krypton have achieved an energy resolution of 3 electron volts. In the near future, the collaboration will switch to using gaseous tritium and measure the helium/tritium mass difference. The final stage of development will use atomic tritium to measure the electron neutrino mass.

LNS researchers are prominent in relativistic heavy-ion physics. The Heavy Ion Group plays a leading role in the CMS experiment heavy-ion program at CERN. LHC operation in 2015 included several weeks of lead–lead collisions to study heavy-ion physics. Figure 4 shows the many particle tracks resulting from a lead–lead collision in the CMS detector, which has a cylindrical volume. The tracks, in green, emanate from the point where the collision occurred and spread out in all directions, with the degree and sign of curvature related to the particle's momentum and charge. Energy deposited by some of the particles in the CMS calorimeters is displayed by a red or blue tower at the location of the calorimeter hit, with the height of the tower reflecting the energy of the particle.

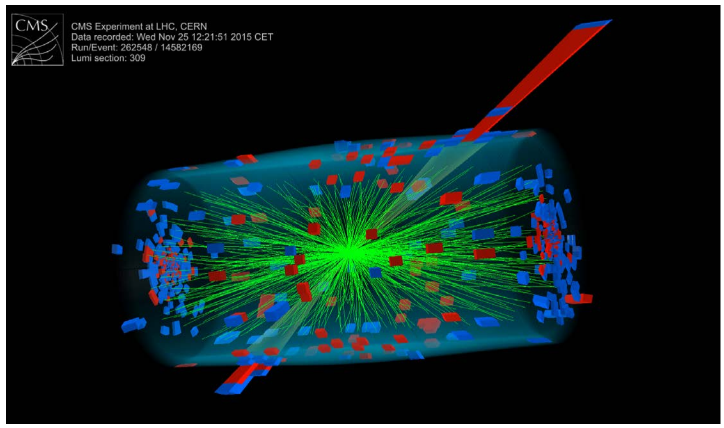

Figure 4: One of the first heavy-ion collisions at high beam energy recorded by CMS in 2015. The green lines represent particle tracks in the CMS detector, while the red and blue towers represent hits in the CMS calorimeters; the height of the tower reflects the particle's energy. Two jets can be seen leaving the collision point in opposite directions, with the asymmetry in energy caused by in-medium parton energy loss.

To allow efficient data taking at higher energy and higher collision rates, the MIT group made major changes to the detector trigger system, silicon tracker readout, and online and offline reconstruction algorithms. Physics results in FY16 include new measurements of D meson and charged hadron spectra, which will elucidate the microscopic nature of parton interactions with the quark-gluon plasma produced in heavy-ion collisions. The group has also joined the sPHENIX collaboration, which is working to upgrade the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in New York. Professor Gunther Roland has been elected co-spokesperson of sPHENIX, which will be used to study jet quenching in heavy-ion collisions, in a manner complementary to CMS.

LNS nuclear physics researchers are leading several important efforts at accelerator facilities in the US and Europe. These facilities include the RHIC, Jefferson Lab, the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee, the Mainz Microtron in Germany, and the Large Hadron Collider beauty LHCb experiment (LHCb) at CERN. The main thrust of these experiments is a detailed understanding of the properties of the proton, the neutron, and light nuclei.

Several experiments (OLYMPUS at the Deutsches Elektronen-Synchrotron in Germany and Q_{weak} at Jefferson Lab) are in the final stages of data analysis, with results expected in 2016. Other experiments are in the development and commissioning stages (GlueX and DarkLight at Jefferson Lab, nEDM at the Spallation Neutron Source). Experiments to measure the elastic electromagnetic form factors of nucleons and the neutron distribution radius in the lead nucleus are running, or preparing to run, with the upgraded 12 GeV beam at Jefferson Lab.

Theoretical Particle and Nuclear Physics

Research at the CTP seeks to extend and unify our understanding of the fundamental constituents of matter. It seeks to advance the conceptual foundations of fundamental physics, especially as applied to the structure and interactions of hadrons and nuclei (new forms of matter that may be created experimentally or observed astrophysically) and to the history and large-scale structure of the universe. There is a growing effort in quantum computation and quantum information. A few examples of recent work are mentioned below.

Nuclear theorists have analyzed the evolution of an ensemble of jets in N=4 supersymmetric Yang-Mills theory, with an initial distribution for the energy and opening angle taken from perturbative quantum chromodynamics (QCD) as they propagate through strongly coupled plasma, as in a heavy-ion collision. They find that each individual jet widens as it propagates, while the opening angle distribution at any given energy is pushed toward smaller angles because wider jets lose more energy. The mean opening angle for jets with a given energy can easily shift toward smaller angles, as experimental data indicate.

A new approach to lattice QCD calculations minimizes the notorious issue of critical slowing down as the continuum limit is approached (i.e., as the lattice spacing gets smaller), thereby significantly speeding up future lattice calculations. Lattice QCD has been used to calculate the hadronic inputs to decay of the Λ_b particle. In combination with experimental measurements of such decays by the LHCb collaboration, this provides a new determination of a Standard Model parameter.

In another area of theoretical nuclear physics, effective field theory is used to calculate experimental quantities for energetic hadrons and hard probes, based on controlled expansions in some useful parameter. MIT theorists and collaborators have recently performed a high-precision re-summed calculation for Higgs production with a jet veto, as LHC experiments make measurements of the Higgs boson using events with a specific number of leptons, photons, and jets. A calculation for Higgs production with zero jets is in good agreement with experimental data.

Particle theorists are active in a wide range of areas, from field theory, supergravity computations, and jet quenching to string theory, dark energy, neutrino masses, quantum computation, and quantum information. They work in collaboration with experimentalists as well as colleagues in condensed matter theory and with MIT's Departments of Mathematics and Electrical Engineering and Computer Science.

Recent projects include a study of the behavior of axion dark matter indicating that a Bose-Einstein condensate would be formed in clumps; a study of hadronic resonances in the limit of a large number of colors in QCD, with implications for novel heavy-quark meson states; the solution of a long-standing problem in general dissipative fluids, using symmetry principles to write down a low-energy effective action; the use of string theory to provide new insights into how gauge fields and matter arise naturally in generic string compactifications; and a study of how gravity in string theory differs from Einstein's gravity. New methods have been developed to distinguish signals of dark matter annihilation from novel astrophysics in the inner Milky Way. First-principles calculations in the QCD of jet substructure agree with data from the CMS experiment.

The quantum computation and quantum information effort is concerned not only with efficient ways to perform quantum mechanics and other types of calculations (e.g., factoring integers), but also with applications such as quantum cryptography.

Physics of High-Energy Plasmas

This effort addresses a broad spectrum of subjects in areas that are relevant to fusion research, astrophysics, and space physics. Specifically, LNS researchers are involved in identifying the properties and dynamics of plasmas that are dominated by collective modes, emphasizing fusion-burning plasmas that are relevant to the upcoming generation of experiments, and high-energy astrophysical plasmas.

MIT-Bates Linear Accelerator Center

DOE provides base support for a research and engineering center where US nuclear and particle physicists, including LNS faculty and their collaborators, develop new instrumentation for frontier research. Funding for specific projects also comes from DOE, NSF, and other universities and laboratories. For example, MIT-Bates Center engineers have developed a design for the spectrometer system for the future Measurement Of a Lepton Lepton Electroweak Reaction (MOLLER) experiment at Jefferson Lab, measuring the parity-violating asymmetry in electron–electron scattering. This experiment will use two toroidal spectrometers, one of which has hybrid coil shapes to provide the necessary magnetic field that is integral to directing very forward-scattered electrons onto fused silica detectors.

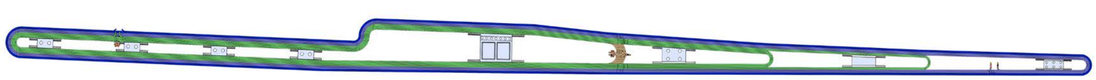

Figure 5: A solid model of a hybrid coil (side view) for use in the future MOLLER experiment at Jefferson Lab. The coil is about 7 m long and 0.3 m across at its widest point. The target would be to the right and the detectors to the left, with the beam centerline below the coil; there are seven coils in total, arranged symmetrically around the beam centerline. The different colors reflect different cooling paths.

Figure 5 shows one hybrid coil with multiple conductor loops, deformed from a classic oval racetrack design. There are four main loops of different lengths, shown in different colors. Gray rectangular pieces are located between the two sides of the loops along the length of the coil to maintain the coil shape when powered.

MIT-Bates Center physicists, engineers and technicians have made contributions to many of the experiments discussed above. In addition, research using particle accelerators is a major focus at the MIT-Bates Center, with MIT scientists and engineers developing and designing new accelerators and accelerator-based systems for both fundamental and applied investigation. A small, 3 megaelectron volt deuteron accelerator used in earlier projects funded by the US Department of Homeland Security is now being used by faculty, scientists, and students in the Department of Nuclear Science and Engineering to develop a technique to identify high-Z materials in cargo. Physicists, engineers, and technicians from the MIT-Bates Center have built a high-intensity polarized electron source with the goal of improving, on average, the currents possible with existing sources by one to two orders of magnitude, with testing and improvements to occur over the next year. Such a source is essential for some versions of a future electron-ion collider, which has been deemed by the US Nuclear Science Advisory Committee to be the next major nuclear physics facility to be built.

The high-performance research computing facility at the MIT-Bates Center supports 70 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power. The facility supports LHC data analysis, lattice QCD calculations, ocean and climate modeling by a group in the Department of Earth, Atmospheric and Planetary Sciences, computational fluid dynamics relative to ship hull design for the MIT Sea Grant program, molecular modeling of polymers by a group in the Chemical Engineering Department, the Laser Interferometer Gravitational-Wave Observatory experiment, the MIT Geospatial Data Center, and other LNS research.

MIT Central Machine Shop

LNS operates the MIT Central Machine Shop as a service center. The Central Machine Shop is widely used across the Institute to build research-related equipment and to perform work for the Department of Facilities and research facilities from off-campus sites. The work ranges from small to large jobs, and includes complex jobs that require precision machining, such as a double gyroid photonic crystal for the Institute for Soldier Nanotechnologies, used to observe Weyl points for the first time.

Figure 6 shows one layer of off-white ceramic, 12 inches square, being drilled at an angle. The ceramic is clamped in place by an aluminum bar. The 588 holes in the layer are drilled at two different angles; each hole is slightly smaller than a dime. Shavings from the drilling have fallen down the ceramic to collect at the bottom.

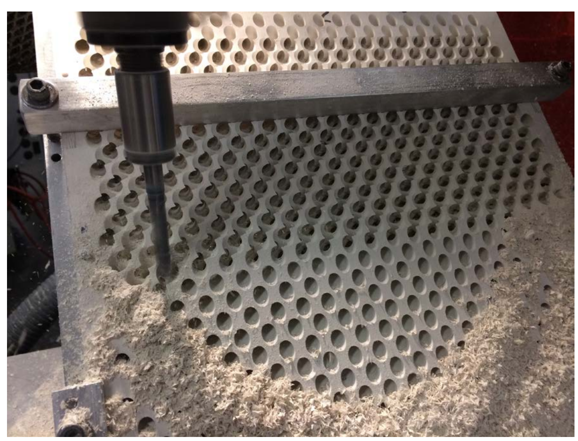

Figure 6: A layer of ceramic being drilled to create a double gyroid photonic crystal for MIT's Institute for Soldier Nanotechnologies, used to observe Weyl points. Each of the 588 holes in the layer is drilled at two different angles; a third angle results from machining 27 grooves in the surface of the layer. The finished photonic crystal consists of 18 such layers.

Another project involved machining components and assembling an autonomous buoy for the Department of Mechanical Engineering. Figure 7 shows a stainless steel sphere with the top cut off, roughly 12 inches in diameter. Three motors and propellers are mounted beneath the hemisphere, pointed at 120 degrees to each other to provide motion in any direction. Electronics for motor control, position sensing, and communication are located inside the hemisphere beneath a clear lid.

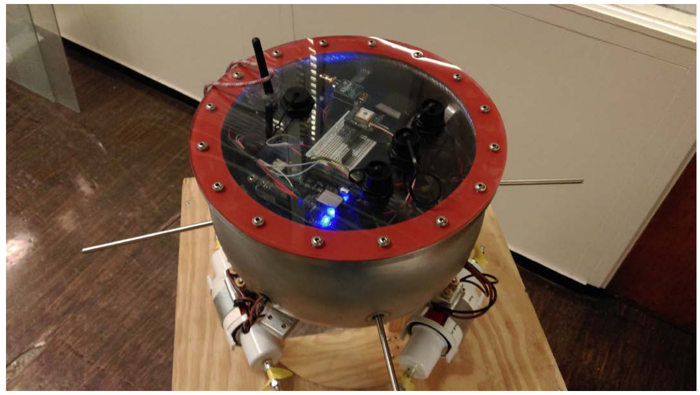

Figure 7: An autonomous buoy created for MIT's Department of Mechanical Engineering.

The buoy is stable and can self-position following simple coordinate-based directions. In the future, a number of these buoys could form a network to investigate an environmental issue, communicating via wireless to share local information and build a larger picture of the issue.

Education

Since its founding, LNS has placed education at the forefront of its efforts and goals. At present, approximately 82 graduate students are receiving their training through LNS research programs. A number of undergraduate students are also heavily involved in LNS research. LNS has educated a significant portion of the leaders of nuclear and particle physics in this country and abroad.

Boleslaw Wyslouch
Director
Professor of Physics