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 Linear Accelerator Center and the Center for Theoretical Physics (CTP). Almost half of the faculty members in the Department of Physics conduct research through LNS. During fiscal year 2017, total research volume was $21.9 million; this was an increase of about $0.6 million from the previous year and more in line with a 10-year average of $22.2 million. Funding came from the US Department of Energy (DOE), the National Science Foundation (NSF), and other sources. The increase in FY2017 was due to the launch of new research programs by several younger faculty and researchers. LNS researchers are successfully pursuing multiple funding opportunities that should maintain or increase research volume in the future. Six LNS junior faculty hold prestigious Faculty Early Career Development Program Awards from DOE and NSF.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at CERN (the European Organization for Nuclear Research) in Geneva, Switzerland; at the Fermi National Accelerator Laboratory 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 seek evidence for physics beyond the Standard Model. This is accomplished either by searching directly for new phenomena or by measuring predicted quantities as precisely as possible, thus testing the Standard Model, which has been very successful in describing a wide variety of phenomena. LNS researchers are playing principal roles in much of this research.

New faculty member Professor Kerstin Perez is developing lithium-drifted silicon detectors for an astroparticle experiment—the General Antiparticle Spectrometer—that will fly on a long-duration Antarctic balloon flight in 2020 to search for antideuterons in low-energy cosmic rays. If cosmic antideuterons are detected, this would signal a new physics; detection would permit a variety of dark-matter models to be tested. The silicon lithium detectors are being developed and tested in a laboratory on the MIT campus, involving a number of students in hands-on research.

Figure 1. A prototype 10-cm diameter, 2.5-mm thick, single-strip silicon lithium detector mounted in a test chamber for calibration. (Photo: Kerstin Perez).

Figure 1 shows a dull yellow circle surrounded by a bright silver-colored band, set in a dull silvery square with the corners cut off, with a tan circuit board mounted in the upper left corner. The circuit board contains a number of electrical components of various colors. The assembly sits inside a silvery chamber, with several fine wires of various colors running from the assembly to access holes in the chamber.

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). The experiment has been collecting data since 2011; it has now collected more than 100 billion cosmic ray events, far more than in the entire previous history of cosmic ray physics. The EMI group leads the data analysis effort and is responsible for proper operation of the spectrometer, a difficult task given the hostile thermal environment of the ISS. Results have been published this year on a comparison of the boron with the carbon flux in cosmic rays. Carbon is one of the nuclei thought to be produced at the sources of cosmic rays (along with helium and oxygen); boron is produced by the collision of one of these "primary" cosmic rays with the interstellar medium. These precise results show that the boron to carbon ratio is well described by a single power law above a rigidity (momentum/charge) of about 50 GV. This could indicate diffusive reacceleration processes in the interstellar medium. Data will continue to be collected on electrons, positrons, protons, antiprotons, helium, and other nuclei until the end of ISS operations, currently scheduled for 2024.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment 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 continues to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos, and is also in the process of constructing a high-intensity ion source to feed the future synchrotron.

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, the massive computing system, detector upgrades, and data analysis. LNS scientists are leading the program to study high-energy, heavy-ion collisions. The collider has by now accumulated a significant data sample at the present energy frontier (13 TeV center-of-mass energy). By the end of Run 2 (2015–2018), LHC will have collected a sample of more than 120 fb^{-1}, that is, about five times more data at an energy almost twice as high as during Run 1 (2010–2012). With the discovery of the Higgs boson in Run 1, LNS researchers are using CMS to search for dark matter (using the signature of missing energy in the detectors) and to measure detailed properties of the Higgs boson. A number of searches and measurements have been completed that expand our horizons, but so far there is no evidence for new physics.

LNS researchers in high-energy and nuclear physics are developing the DarkLight experiment with the help of engineers and technicians at MIT's Bates Research and Engineering Center. The experiment will use the 100 MeV free electron laser beam at the Thomas Jefferson National Accelerator Facility (JLab) 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 was installed at JLab and took data in the summer of 2016. Based on results from that run on the interactions of the accelerated electron beam with the target and magnet, modifications to the target, magnet and vacuum system are being pursued. An experiment to measure the radiative Møller scattering process will run at MIT's High Voltage Research Laboratory using the 3 MeV electron beam there.

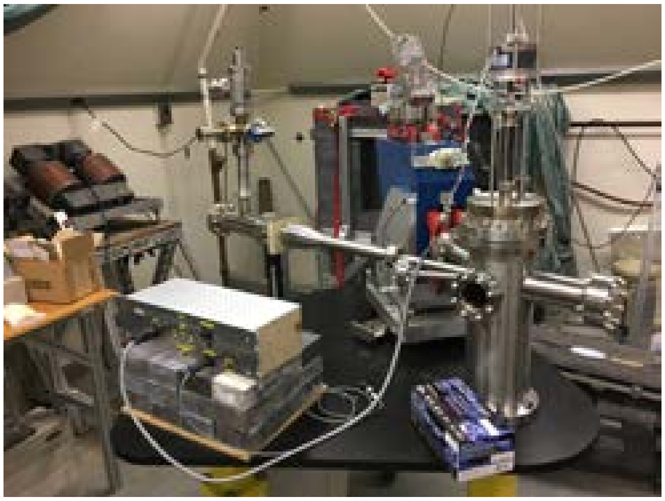

Figure 2: The experimental setup for the DarkLight experiment's measurement of radiative Møller scattering in the MIT High Voltage Research Laboratory. The cylindrical target chamber to the right of the photo is about 15 inches high; the mechanism to move the target ladder extends from the top of the chamber. The blue electromagnet with red coils will analyze the scattered electrons.

Figure 2 shows a 15-cm diameter, 50-cm tall silver-colored vertical cylinder with several rods and a bellows mounted on the top to operate the experiment target. Several silver-colored vacuum pipes extend from the cylinder; a blue wedge-shaped electromagnet with red coils sits behind the target chamber. A platform of gray bricks supports a silver-colored and pale gold box with cables and switches on the front. All the equipment is mounted on a black triangular plate about one meter per side; the plate is supported by three yellow legs. This process is an important background for the DarkLight experiment, and the radiative Møller scattering has never been measured experimentally.

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 fields.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies seeking to measure the neutrino 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 in Japan, searching for neutrinoless double beta decay. If double beta decay is observed, this would imply that the neutrino is its own antiparticle. Part of this search involves the development of novel detector techniques, including the use of quantum dots and the development of scintillating bolometer detectors. MIT physicists are 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 and the detector system has seen "first light," with electrons traveling from one end of the experimental apparatus to the other, a distance of 70 meters. 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 eV. 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.

Researchers in the Laboratory for Nuclear Science are prominent in relativistic heavy-ion physics. The heavy-ion group plays a leading role in the CMS experiment's heavy-ion program at CERN; LHC operation in 2016 included several weeks of proton–lead collisions. Physics results in FY2017 included the highest particle multiplicity density ever observed in non-single-diffractive proton–lead collisions, studies of jet quenching and jet structure using jet+photon and jet+Z0 events, and studies of heavy quark production. 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. The sPHENIX upgrade will be used to study jet quenching in heavy ion collisions, in a fashion complementary to CMS.

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

The OLYMPUS experiment, which ran at the Deutsches Elektronen-Synchrotron in Germany, was designed to measure the contribution of a two-photon exchange to elastic lepton-proton scattering. The collaboration has published results on the ratio of positron-proton to electron-proton elastic scattering that show a small two-photon contribution, with an indication of a more significant contribution at higher momentum transfers. The observed results are significantly below theoretical predictions.

The Qweak experiment, which ran at JLab, is in the final stages of data analysis, with results expected in 2017. Other experiments are in the development and commissioning stages, including GlueX and DarkLight at JLab, and a neutron electric dipole moment experiment at the Spallation Neutron Source. Experiments to measure the elastic electromagnetic form factors of nucleons, the neutron distribution radius in the lead nucleus, and short-range correlations between nucleons inside nuclei are running, or being prepared to run, with the upgraded 12 GeV beam at JLab.

Theoretical Particle and Nuclear Physics

Research at the Center for Theoretical Physics seeks to extend and unify our current understanding of fundamental physics.

The Standard Model of particle physics, recently completed with the discovery of the Higgs boson, provides a powerful theoretical framework for describing most aspects of fundamental physics that can easily be accessed with existing experiments. However, this model describes only 5% of the mass-energy in the observed universe, does not explain how gravity fits into the framework of quantum physics that underlies the standard model, does not explain cosmology or the very early universe, and contains roughly 19 independent numerical parameters and a set of forces and particles that as yet cannot be explained by any more fundamental theory. Furthermore, within the Standard Model there are major practical and conceptual challenges in calculating even some simple quantitative features, such as the mass of the proton (which is a bound state of quarks), due to the strong coupling of the strong nuclear force. And there are many puzzles related to quantum physics, black holes, and other accepted features of the Standard Model and Einstein's theory of general relativity that remain to be addressed.

Faculty in the center are working at the forefront of research on all these questions, including related problems that connect to mathematics, condensed matter physics, astrophysics, and quantum information. The CTP is unusual among university groups in both its breadth and its unity. A few examples of recent work are mentioned below.

The nuclear theory group focuses on trying to understand the structure and interactions of nuclei, which are composed of quarks that interact through the quantum chromodynamic force (QCD). The lattice QCD (LQCD) effort, led by junior faculty member William Detmold, focuses on calculating the properties and interactions of light nuclei. The first calculations of the proton-proton fusion process (relevant for energy production in the sun) and the weak decay of tritium were performed this year by CTP researchers; they have also made the first calculations of the simplest nuclear transition that contributes to double beta decay. CTP nuclear theorists have developed a hybrid strong-weak coupling approach to jet quenching, understanding how a parton fragments into a shower of partons and then how those partons propagate through strongly coupled plasma, as in a heavy-ion collision. They have used this model to make predictions for a number of observable gamma-jet phenomena; these predictions have been confirmed by experimental data from LHC. In another area of theoretical nuclear physics in which the MIT group has a leading role, effective field theory is used to calculate experimental quantities for energetic hadrons and hard probes on the basis of controlled expansions in some useful parameter.

CTP high-energy theorists are active in a wide range of areas, including quantum field theory, supersymmetry and supergravity, string theory, jet quenching, dark matter, dark energy, neutrino masses, and connections to condensed matter physics. Members of this group work in collaboration with experimentalists as well as colleagues in condensed matter theory and MIT's Department of Mathematics and Department of Electrical Engineering and Computer Science. A current focus of theoretical research, particularly for Jesse Thaler (recently granted tenure) and junior faculty member Tracy Slatyer, is the 80% of matter in the universe that is "dark" and not described by the Standard Model. Recent projects and results in this area include development of tools to test the impact of dark matter annihilation on the cosmic microwave background, new techniques for dark matter searches, and novel paradigms for describing how dark matter interacts with the visible universe. Slatyer's recent research has also uncovered evidence for a hitherto unknown and unexpected population of spinning neutron stars in the heart of the Milky Way.

CTP faculty members who are working on quantum gravity, string theory, and cosmology have used new mathematical techniques to attain a coarse picture of the broadest set of string theory solutions, or vacua, that have been explored. They have identified new and unexpected structure in this landscape, as well as exploring dynamics in the landscape and inflationary models, and the rate of production of primordial black holes in the context of hybrid inflation models. Work on effective field theories for non-equilibrium systems has yielded a systematic framework for fluctuating hydrodynamics. The new framework is expected to have a wide range of applications, including dynamical critical phenomena, non-equilibrium phase transitions, heavy ion collisions, and turbulence. Recent CTP work on a project known as the Cosmic Bell experiment examined whether what Einstein called the "spooky action at a distance" of quantum physics can be shown not to depend on hidden correlations; it is hoped to do this by studying the quantum behavior of pairs of photons from stars that lie in different directions in the sky.

Quantum information and quantum computation is a growing effort in CTP. This research program is concerned not only with efficient ways to perform quantum computations (e.g., factoring integers), but also with applications such as quantum cryptography and with basic theoretical questions about quantum information and quantum entanglement. Junior faculty member Aram Harrow carries out leading work in these areas. Among other findings, Harrow has recently shown that a quantum computation method based on adiabatic quantum tunneling cannot universally outperform any possible classical computer. He has also shown that quantum entanglement is less fragile than previously thought by demonstrating that entanglement in simple interacting quantum systems with topologically nontrivial entanglement can survive deletions in ways previously not thought to be possible.

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, in particular fusion-burning plasmas relevant to the upcoming generation of experiments and high-energy astrophysical plasmas.

MIT-Bates Linear Accelerator Center

DOE provides basic 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, universities and laboratories, and industry. For example, engineers and technicians from MIT's Bates Linear Accelerator Center designed and are building two optical boxes to focus Cerenkov light from repurposed quartz bars onto phototubes. The optical boxes will provide improved particle identification for the GlueX experiment at the Jefferson Accelerator. Furthermore, MIT-Bates physicists, engineers, and technicians have made contributions to many of the experiments mentioned earlier.

In addition, research using particle accelerators is a major focus at the Bates Linear Accelerator Center, with MIT scientists and engineers developing and designing new accelerators and accelerator-based systems for both fundamental and applied investigation. Physicists, engineers, and technicians have built a high-intensity polarized electron source with the goal of improving on the average 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 the US Nuclear Science Advisory Committee identified as the next major nuclear physics facility to be built.

The high-performance research computing facility at Bates has 70 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power. The facility supports the computing necessary for LHC data analysis, LQCD calculations, and 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; work at the MIT Geospatial Data Center; and other LNS research uses.

MIT Central Machine Shop

The Laboratory for Nuclear Science operates the MIT Central Machine Shop as a service center. The machine shop is widely used across the Institute to build research-related equipment, as well as to perform work for the Department of Facilities and research facilities at off-campus sites. The work ranges from small jobs to large and complex jobs that require precision machining, such as a sample storage “tombstone” for the Materials Processing Center. The tombstone is mounted on a post inside a vacuum chamber; samples are stored on all four sides of the tombstone, safely out of the way while experiments are done on one sample.

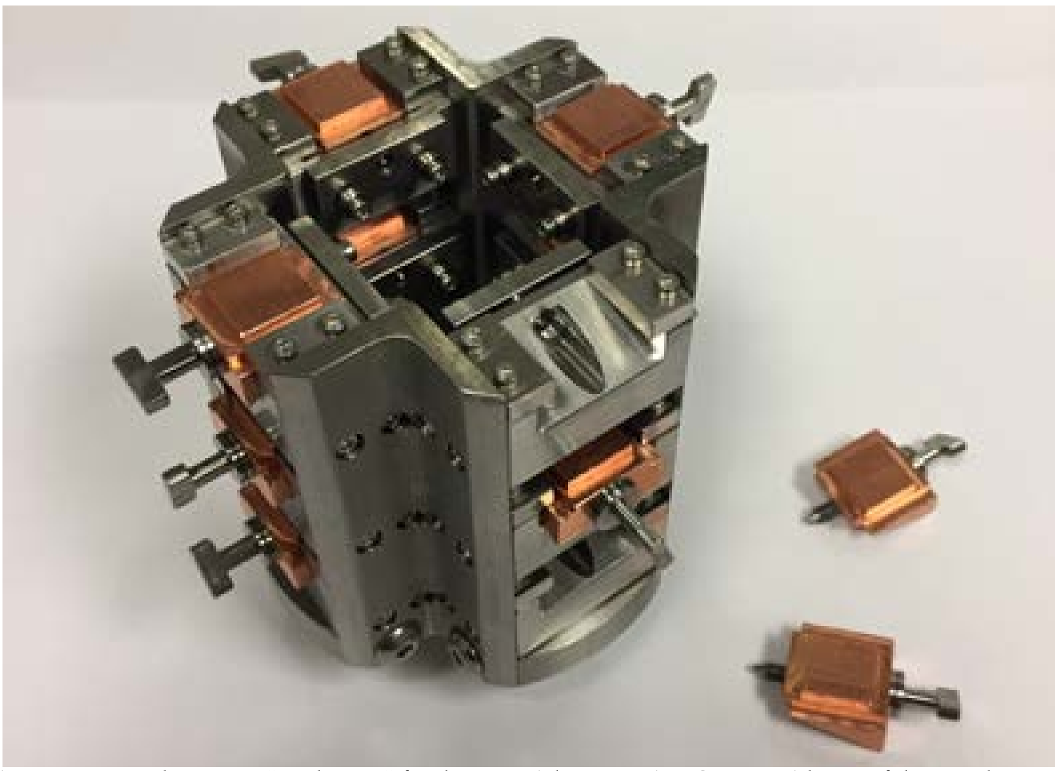

Figure 3: A sample storage “tombstone” for the Materials Processing Center, with two of the sample storage cartridges removed. The tombstone is about 2.5 inches high and 3 inches wide. Photo: Andrew Gallant.

Figure 3 shows a roughly cubical silver- and copper-colored shape, with a horizontal cross section that takes the shape of a cross with short arms; the center of the cross is hollow. Each cross can hold three wedge-shaped copper blocks slotted into its face; each has a stainless steel key that locks the block into place. (Two copper blocks were removed for the photograph; they sit to the right of the cross. A number of setscrews hold the components together.)

Another project involved machining components for a double-walled test chamber for the Department of Chemistry. The test chamber was inserted into a commercial vacuum oven. A cooling coil wound around the top of the test chamber keeps everything external to the vacuum oven cool.

Figure 4: A double-walled test chamber for the Department of Chemistry on the left; this will be inserted into the commercial vacuum oven on the right. The test chamber is approximately 16 inches high and 6.5 inches in diameter, including the ceramic rods that extend from the top.

Figure 4 shows a tan cube, which is the vacuum oven, labeled Thermo Scientific Lindberg Blue M; the experiment access port in the top is covered by a white disk with a black and silver-colored tube in the center. Next to the cube is the experimental insert, consisting of a dark gray can with a silver-colored top, from which protrude a number of silvery tubes, some with tan ceramic rods inserted. Several windings of copper tubing are around the top of the can, with the two ends of the winding out to the left. The vacuum oven and experimental insert sit on blue paper on a concrete floor.

Education

Since its founding, LNS has placed education at the forefront of its work and goals. In the past year, approximately 86 graduate students received their training through LNS research programs. A number of undergraduate students were 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.

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