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 Bates Accelerator/Research and Engineering Center and the Center for Theoretical Physics (CTP). Almost half of the faculty of the Department of Physics conduct research through LNS.

During FY2015, 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 $19.1 million, a decrease of about $2.5 million from the previous year. This was caused by reductions in federal funding in some areas (theoretical high energy physics, for example), the conclusion of an experiment construction project (the STAR Intermediate Silicon Tracker), an increased number of student and postdoctoral fellowships, and planned retirements. LNS researchers are successfully pursuing multiple funding opportunities that should maintain or increase research volume in the future. Three junior faculty members received Early Career/CAREER Awards from DOE and NSF this year; there are now seven LNS junior faculty who hold these prestigious awards.

After successfully serving as director of LNS for nine years, Professor Richard Milner will step down on June 30, 2015. Professor Boleslaw Wyslouch has been appointed as the new LNS director.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at CERN in Geneva, Switzerland, and at the Fermi National Accelerator Laboratory (Fermilab) in Illinois. 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 the CMS. After a shutdown for maintenance and upgrades, the LHC is now running at 13 TeV, nearly the design collision energy, and is moving toward reaching the design luminosity. With the discovery of the Higgs boson accomplished, LNS researchers plan to use 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. Guillelmo Gómez-Ceballos has been promoted to principal research scientist.

The Alpha Magnetic Spectrometer experiment (AMS-02), led by the 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, and now has collected more than 60 billion cosmic ray events. The EMI group leads the data analysis effort and is also responsible for proper operation of the spectrometer, a critical and difficult undertaking given the hostile thermal environment of the ISS. Results have been published this year on the positron fraction, the electron and positron fluxes, the combined electron and positron flux, and the proton flux. These results are consistent with dark matter collisions and cannot be explained by existing models of the collision of ordinary cosmic rays. There are many new models showing that the results may be explained by new astrophysical sources (such as pulsars) or new acceleration and propagation mechanisms (such as supernova remnants). Data will continue to be collected on these particles, as well as on antiprotons, helium, and other nuclei, for the next 7–15 years. Xudong Cai, Vitali Choutko, and Andrei Kounine have been promoted to the rank of senior research scientist.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment (MicroBooNE) and related experiments at Fermilab. As part of this work, the group has made important improvements to liquid argon time projection chambers, especially in the areas of high voltage surge systems and light collection. MicroBooNE is expected to collect data in 2015. The group also continues to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos, and is joining the IceCube collaboration to search for sterile neutrinos in an experiment at the South Pole.

LNS researchers have designed and built a Cubic Meter Dark Matter Time Projection Chamber (DMTPC) with the help of engineers at the Bates Accelerator/Research and Engineering Center. The DMTPC seeks direct detection of dark matter particles by observing recoiling nuclei from their collisions with carbon tetrafluoride gas molecules in the detector. It is undergoing testing and commissioning at MIT before eventual deployment to an underground laboratory.

Figure 1: The cryostat for the MicroBooNE liquid argon time projection chamber (LArTPC) during installation of the last wavelength-shifting plate in front of the light collection phototubes (along the right side of the cylinder), before insertion of the LArTPC (background).

Experimental Nuclear Physics

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

In fundamental properties, LNS nuclear physicists are studying neutrinos, 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 playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment at Karlsruhe, Germany, and in the Project 8 experiment, both of which are meant 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's mass even more precisely using frequency measurements. This year, Project 8 became the first experiment to detect the cyclotron radiation from a single relativistic electron. These first measurements have been made on electrons emitted by a radioactive isotope of krypton. In the near future, the collaboration will switch to using gaseous tritium. A new MIT faculty member is part of the CUORE collaboration at Gran Sasso, Italy, and the KamLAND-Zen collaboration at the Kamioka Observatory, Japan, searching for neutrinoless double beta decay. If observed, this would imply that the neutrino is its own antiparticle. Part of this search involves development of novel detector techniques, including the use of quantum dots.

LNS researchers are prominent in relativistic heavy-ion physics. The Heavy Ion Group plays a leading role in the CMS heavy-ion program at CERN, including overseeing the measurement of exclusive B mesons. A key to understanding the properties of nuclear

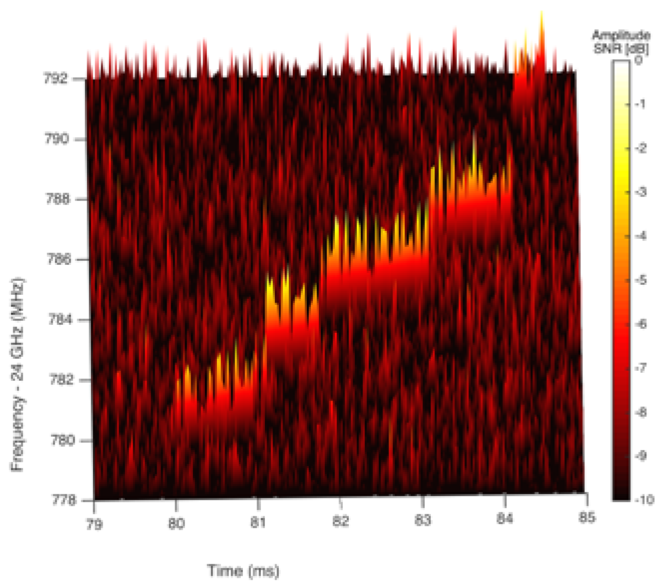

Figure 2: A plot of detected cyclotron frequency (related to the kinetic energy) of a single electron versus time, with the vertical axis and color-coding indicating signal strength (noise in the smaller black/red peaks, the single-electron signal in the larger orange/yellow peaks). The frequency increases slowly as the electron loses energy by emission of cyclotron radiation. The frequency jumps when the electron collides with residual gas in the detector and loses energy..

matter at the highest temperatures, the quark-gluon plasma, is to characterize the mass dependence of quark and gluon energy loss as they traverse the plasma produced in high energy heavy-ion collisions. Of particular importance are b-quarks, as their mass is an order of magnitude larger than the typical momentum scales given by the plasma temperature. The CMS experiment has taken a major step forward with the first measurement of exclusive B-hadron decays in nuclear collisions, studying proton-lead collisions at 5 TeV at the LHC and performing the first study identifying these decays in lead-lead collisions. For proton-lead collisions, B-meson production was found to be unmodified with respect to theoretical expectations, which provides a critical reference for the future B-physics program in heavy-ion collisions at the LHC.

LNS nuclear physics researchers are leading several important efforts at accelerator facilities in the US and Europe. These facilities include the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in New York, the Thomas Jefferson National Accelerator Facility (JLab) in Virginia, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory in Tennessee, the Mainz Microtron and the Deutsches Elektronen-Synchrotron (DESY) in Germany, and the LHC experiment 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 DESY and Q_{weak} at JLab) are in the final stages of data analysis, with results expected in the next year. Other experiments are in the development and commissioning stages (GlueX and DarkLight at JLab, the Neutron Electric Dipole Moment Experiment at SNS). Experiments to measure the elastic electromagnetic form factors of nucleons and the neutron distribution radius in the lead nucleus are preparing to run with the upgraded 12 GeV beam at JLab.

The STAR experiment at RHIC will now be able to detect particles containing heavy quarks using a new detector component, the Heavy Flavor Tracker (HFT). MIT physicists and engineers led the effort to build the Intermediate Silicon Tracker (IST) component of the HFT, consisting of 24 ladders of silicon pad sensors with a total channel count of 110,592 active pads. In 2015, the HFT collected about 1.2 billion events, and the IST operated with more than 95% functional channels and a hit efficiency of more than 98%.

Development of a polarized ^{3}He ion source for RHIC has continued with establishment of a ^{3}He polarization laboratory at BNL. Polarizations of the order of 80% at high magnetic fields have been measured.

Theoretical Particle and Nuclear Physics

Research at the CTP seeks to extend and unify our understanding of the fundamental constituents of matter. They seek 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.

Lattice quantum chromodynamics (LQCD) calculations of light nuclear systems in the presence of strong magnetic fields have led to extractions of the magnetic moments of the deuteron, ^{3}He and the triton, and the polarizabilities of all nuclei up to atomic number A=4. These calculations have also resulted in an ab initio determination of the short distance contributions to the neutron capture process (), an important first stage in Big Bang nucleosynthesis and a milestone for the understanding of nuclear processes from first principles. LQCD has also been used to study the heavy baryon spectrum.

In another area of theoretical nuclear physics, a new effective field theory framework has been developed that describes forward scattering processes and factorization violation in hard scattering collisions. It can be used to explore the physics of the underlying event and multi-parton scattering, and also has ties to the description of collisions in medium for the LHC and RHIC. Another project studies jet quenching in heavy ion collisions, where a hybrid strong/weak coupling approach provides a good description of single and dijet data sets from the LHC.
Studies have also been made of charge-changing and neutral current neutrino reactions with nuclei at high energies where relativistic effects are important, for comparison with future measurements at Fermilab.

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 with colleagues in condensed matter theory and the Departments of Mathematics and Electrical Engineering and Computer Science.

The quantum computation and quantum information effort has grown in the past two years with the addition of a new faculty member. The field 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 relevant to the upcoming generation of experiments, and high-energy astrophysical plasmas.

MIT-Bates Linear Center

DOE provides base support for a research and engineering center where 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, engineers at the MIT-Bates Linear Accelerator Center have begun an assessment of the suitability of an existing atomic beam source of polarized ^{3}He for the nEDM experiment at the SNS. . Furthermore, MIT-Bates Center physicists, engineers and technicians have made contributions to many of the experiments discussed above.

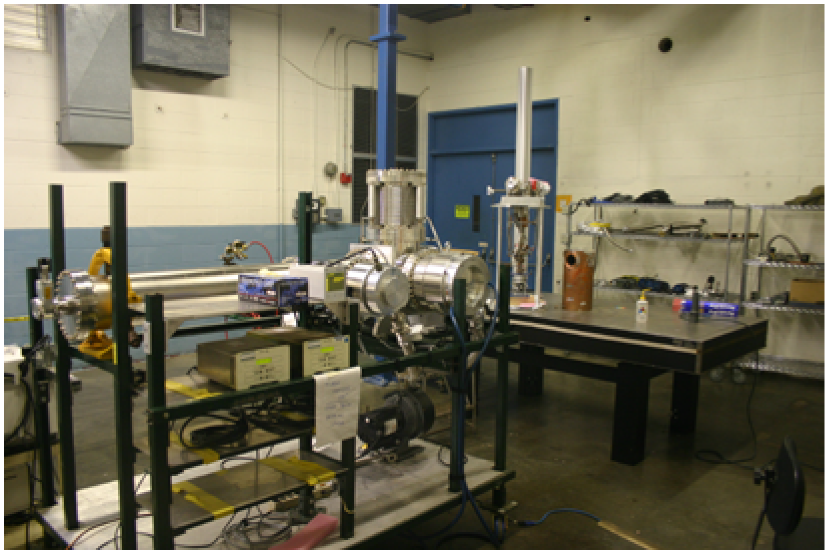

Figure 3: The atomic beam source for the nEDM experiment being assembled for testing at the MIT-Bates laboratory

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 MeV deuteron accelerator used in previous DHS-funded projects 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. MIT-Bates Center 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.

The high-performance research computing facility at the MIT-Bates Center supports 71 water-cooled racks, each with up to 10 kW of cooling power. The racks are used for LHC data analysis, LQCD 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, and the MIT Geospatial Data Center. They are useful in other LNS research as well.

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, as well as for work for the Department of Facilities; research facilities from off-campus sites also use the shop. The work ranges from small to large jobs, or complex jobs that require precision machining, or both, such as a traveling wave tube amplifier for the Plasma Science and Fusion Center or the sediment flume tank for the Department of Civil and Environmental Engineering to study sediment transport in vegetated channels.

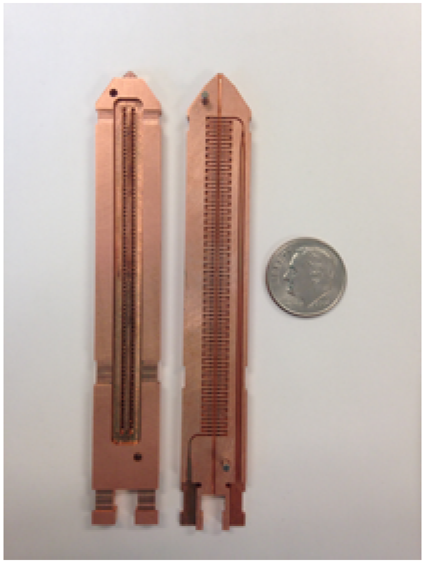

Figure 4: A traveling wave tube amplifier made in the Central Machine Shop for MIT's Plasma Science and Fusion Center, to test the suitability of oversized devices for stable amplification of RF waves.

Figure 5: A sediment flume tank made in the Central Machine Shop for Prof. Nepf's lab in MIT's Department of Civil and Environmental Engineering, to study sediment transport in vegetated channels.

Education

Since its founding, LNS has placed education at the forefront of its goals. At present, approximately 79 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.

Richard G. Milner
Director
Professor of Physics