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. This includes activities at the MIT-Bates Linear Accelerator Center and the Center for Theoretical Physics. Almost half of the Department of Physics faculty conduct research through LNS. During FY2013, total research volume using funding provided by the US Department of Energy (DOE), the National Science Foundation, the Army Research Office, and other sources was $21.0 million, a decrease of about $1.6 million from the previous year. Some of the decrease is due to a reduction in DOE funding associated with the FY2013 federal budget sequestration and some to a natural reduction in expenses associated with the completion of the Alpha Magnetic Spectrometer.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at the European Organization for Nuclear Research (CERN), in Geneva, Switzerland. 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 playing principal roles in much of this research.

The Alpha Magnetic Spectrometer experiment (AMS-02) is designed to look for cosmic antimatter and evidence of dark matter by operating a large 6,717 kg magnetic spectrometer above Earth's atmosphere. The international AMS collaboration consists of more than 500 scientists (primarily particle physicists) led by the Electromagnetic Interactions Group (EMI) within LNS. The AMS-02 spectrometer was launched on the shuttle *Endeavour's* last mission, STS-134, to the International Space Station (ISS), on May 16, 2011, and delivered to the space station on May 19. All systems are functioning as intended and data collection began shortly after arrival at the ISS. Data collection by AMS is planned for the next nine to 17 years. In the first two years of operation, AMS has collected over 30 billion events. Systematic analysis of the data is under way, led by EMI. The first AMS result on the positron fraction in cosmic rays was published in *Physical Review Letters* in April 2013 and selected for a Viewpoint in *Physics* and an Editor's Suggestion. The group is also responsible for proper operation of the spectrometer, a critical and difficult effort given the hostile thermal environment of the ISS.

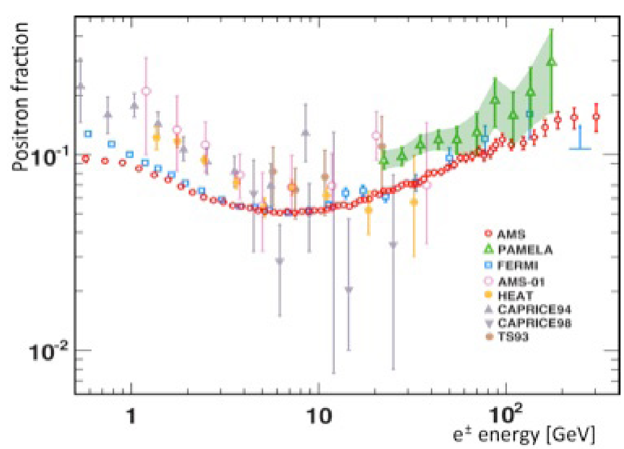

Figure 1. A comparison of AMS results on the positron fraction in cosmic rays with recent published measurements. With its magnet and precision particle detectors, high accuracy, and statistics, the first result of AMS—based on approximately 10% of the total data expected—is clearly distinguished from earlier experiments.

LNS researchers are playing a major role in the Compact Muon Solenoid (CMS) and ATLAS experiments at the Large Hadron Collider, or LHC, at CERN. These experiments are taking data that probe the high-energy frontier of physics and search for new physics beyond the Standard Model. In the CMS experiment, LNS scientists are engaged in data acquisition and distribution systems, detector upgrades, and data analysis; in ATLAS, the effort is concentrated mainly on muon detection systems. LNS scientists are also leading the program to study high-energy heavy-ion collisions with CMS. The initial LHC efforts were focused on detecting the Higgs particle, which is a key to the puzzle of how particles develop mass. In July 2012, both CMS and ATLAS announced discovery of a boson with a mass of approximately 125 GeV/c^2, in the mass range where the Higgs was expected to appear. Attention has now turned to measuring the properties of this Higgs-like particle, to confirm whether it is indeed the Standard Model Higgs. Data collection at LHC continued through early 2013, and LHC is now in a major shutdown for a reliability upgrade to achieve the design collision energy of 14 TeV. The experimental equipment is also being upgraded, with LNS researchers taking the lead in several areas.

Development of new experimental techniques is an important component of LNS research, including development of unique detectors used to search for dark matter. The prototype 10-liter Dark Matter Time Projection Chamber was installed in the underground laboratory at DOE's Waste Isolation Pilot Plant (WIPP), near Carlsbad, NM, and is operating there to understand the intrinsic backgrounds of the detector. This type of detector seeks direct detection of dark matter particles by observing recoiling nuclei as they collide with gas molecules in the detector. A larger 20-liter detector has been built with lower background materials and is undergoing surface testing and calibration at MIT. This detector will be installed at WIPP in fall 2013. An even larger 1 m^3 detector is currently being designed based on improvements suggested by operating experience with the 10- and 20-liter detectors. The 1 m^3 detector is expected to be built in the next year.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment (MiniBooNE) and related experiments at Fermilab and at the Chooz reactor in France. MicroBooNE, the successor to MiniBooNE, will be installed in fall 2013. The group is also pursuing a staged development of a high-powered synchrotron to produce large quantities of neutrinos, with the eventual goal of pairing this synchrotron with an existing neutrino detector such as KamLAND. The first stage of the development is in progress, with beam from a new, very intense ion source being characterized in a test cyclotron magnet at Best Cyclotron Systems in Vancouver, Canada.

Experimental Nuclear Physics

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

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 in New York, the Thomas Jefferson National Accelerator Facility (JLab) in Virginia, the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee, and the Mainz Microtron and Deutsches Elektronen-Synchrotron (DESY) in Germany. The main thrust of these experiments is a detailed understanding of the properties of the proton, the neutron, and light nuclei.

The OLYMPUS experiment to determine fundamental aspects of electron and positron scattering from the proton is being led by LNS researchers. OLYMPUS uses many elements of the Bates Large Acceptance Spectrometer Toroid, which was utilized at MIT-Bates from 2003 to 2005 to carry out a program of precision measurements of elastic and quasi-elastic form-factors. A new target system for OLYMPUS was designed and built at MIT-Bates, as well as new detectors supplied by LNS and other collaborators. Data collection at the DORIS electron/positron storage ring at DESY began in February 2012 with a one-month test run. The data-taking phase of the experiment was successfully completed with a two-and-a-half-month run that ended in early January 2013. The data are currently being analyzed, with results expected in early 2014.

An investigation of the spin structure of the proton is being made using the Solenoidal Tracker at RHIC (STAR) detector in polarized proton-proton collisions. A new detector subsystem for STAR, the Forward GEM Tracker, was completed at MIT-Bates and installed in STAR in fall 2012, in time for the 2012–2013 polarized proton-proton run. This system greatly increases the acceptance for detection of charged W-bosons; recent results from STAR suggest that the contribution by virtual antiquarks inside the proton toward the spin of the proton will be able to be measured through the detection of charged W-bosons in polarized proton-proton collisions. Another upgrade of the STAR detector system, the Heavy Flavor Tracker, will be completed in fall 2013, with one element, the Intermediate Silicon Tracker, being developed by LNS physicists and MIT-Bates engineering and technical staff.

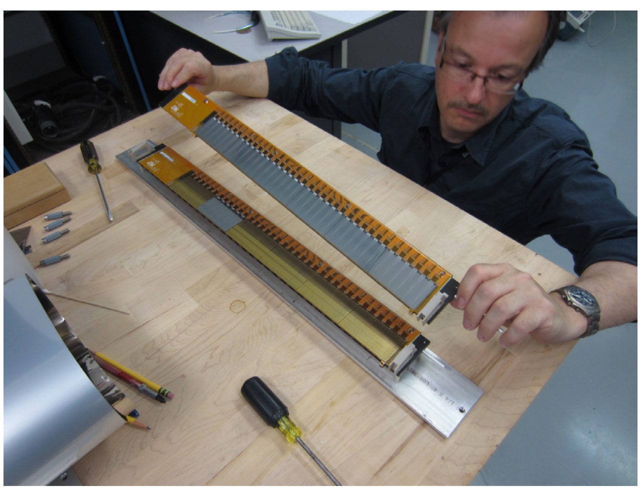

Figure 2. Two staves of the STAR Intermediate Silicon Tracker being test-fit in an assembly jig by LNS Principal Research Scientist Gerrit van Nieuwenhuizen.

The Q_{weak} experiment at JLab completed its data acquisition phase in May 2012. The Q_{weak} toroidal spectrometer was engineered, constructed, and commissioned at the MIT-Bates Research and Engineering Center. The goal is a precision measurement of parity-violating electron scattering to measure the weak charge of the proton, challenge predictions of the Standard Model, and search for new physics. Analysis of the first data set (4% of the total data set) is complete, with publication of the initial result expected in summer 2013. Analysis of the full data set is in progress. LNS researchers are participating in development of a new experiment at JLab, GlueX, to study the light-quark meson spectrum. This includes design and construction of a Cerenkov detector for particle identification, a software trigger system, and development of analysis techniques.

A new effort to search for dark matter using the 100 MeV JLab free electron laser (FEL) has been launched by both experimental and theoretical nuclear and high-energy physicists from LNS. New models suggest dark matter interacts through a "dark force," carried by a GeV-scale particle. The DarkLight experiment would search for this proposed light boson carrier through its decay to an electron-positron pair. A test run in summer 2012 verified the compatibility of the FEL beam with the required narrow aperture (2 mm) target tube, running a 4.3 mA beam through a 2-mm-diameter aperture in a 127-mm-long aluminum block with losses of less than six parts per million. The experiment has received full approval from the JLab program advisory committee. Design of the target and detector systems is proceeding, and funding for detailed design and construction of the experimental equipment will be sought from DOE.

LNS researchers are prominent in relativistic heavy-ion physics. The principal goal of this field has been to investigate the existence and properties of the quark-gluon plasma, a state of matter that exists at temperatures and densities vastly higher than those present in normal matter and that may have been present in the very early universe. The Heavy Ion Group plays a leading role in the CMS experiment heavy-ion program at CERN in physics analysis, experiment operation, and spectrometer improvements. The group will use CMS heavy-ion collision data to answer three questions important to the field: What are the initial conditions in heavy-ion collisions and what is the role of the color glass condensate? What are the properties of the near-ideal liquid produced in heavy-ion collisions and how does it evolve from the initial conditions? What is the mechanism of jet quenching in high-density matter? During the past year, a number of papers have been written using the full 2011 Pb-Pb collision data set and 2012–2013 proton-Pb and proton-proton collision data sets, including the first measurement of absolute quark energy loss using isolated photon-jet correlations in heavy-ion collisions and the discovery of long-range near-side angular correlations in high-multiplicity proton-Pb collisions.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, playing a leadership role in the Karlsruhe Tritium Neutrino experiment in Karlsruhe, Germany. The experiment will take a new precise measurement of the mass of the electron neutrino using the endpoint of the electron energy spectrum from tritium beta decay. LNS researchers have developed the simulation program for the full experiment. They have also, with the assistance of engineers and technicians at MIT-Bates, built the passive shield and active veto system for focal plan detector, as well as calibration systems. Tests of the veto system have measured the veto efficiency at 97%, better than the required 95%. Full experiment commissioning is under way. The LNS Neutrino Group is also developing a novel technique to measure the electron neutrino mass even more precisely using frequency measurements.

Theoretical Nuclear and Particle Physics

Research at the Center for Theoretical Physics 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. A few examples of recent work are mentioned below.

MIT theorists have developed a new method for determining theoretical uncertainties in Quantum Chromo-Dynamics (QCD) calculations of inclusive hadronic jet production cross sections. This plays an important role in establishing exclusion limits for the Higgs search at LHC mentioned above. They have also developed a new event-shape observable called N-jettiness that can be used to define events at hadron colliders that contain N jets.

MIT theorists are analyzing the propagation of a beam of gluons through a strongly coupled plasma, such as that formed by relativistic heavy-ion collisions. In the model, the gluon beam is quenched but does not spread in angle or shift toward softer momenta. This is reminiscent of the behavior of jets as measured by CMS and ATLAS in heavy-ion collisions at LHC; these jets lose energy without a significant change in their angular or momentum distributions.

Lattice QCD aims to obtain a quantitative, predictive understanding of the quark and gluon structure of the nucleon. MIT physicists have been leaders in this scientific computation effort for many years. Recent successes include the calculation of the binding energies of a large number of light nuclei and hypernuclei, albeit with unphysically heavy quarks, and the determination of hyperon-nucleon phase shifts, providing QCD constraints on the equation of state in dense nuclear environments.

Another important area of nuclear theory research is in electroweak probes and interactions. MIT theorists have demonstrated the importance of meson exchange current contributions in intermediate-energy neutrino and antineutrino reactions with nuclei. An effort in the area of parity-conserving and parity-violating electron-proton scattering has applications both for understanding current experimental results and for planning experiments at a possible future electron-ion collider.

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, and quantum information. They work in collaboration with experimentalists as well as colleagues in condensed matter theory, and with the Department of Mathematics and the Department of Electrical Engineering and Computer Science.

Physics of High-Energy Plasmas

Research in the physics of high-energy plasmas 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 Accelerator Center

For three decades, the focus of LNS activities in hadronic physics was the MIT-Bates Linear Accelerator Center, operated by LNS for the US Department of Energy as a national user facility. In 2005, MIT-Bates transitioned from a national user facility for nuclear physics to an MIT-LNS research center. DOE provides base support for a research and engineering center where LNS faculty and their collaborators develop new instrumentation for frontier research. MIT-Bates 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 MIT-Bates, with MIT scientists and engineers developing and designing new accelerators and accelerator-based systems for both fundamental and applied investigation. Recently, MIT-Bates personnel collaborated with an industrial partner in development of a system for scanning cargo for hazardous material for the US Department of Defense. MIT-Bates physicists, engineers, and technicians are developing 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. Such a source is essential for some versions of a future electron-ion collider.

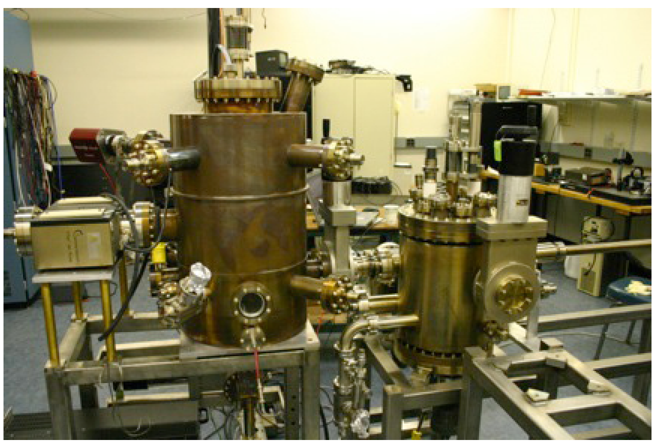

Figure 3. The high-intensity polarized electron source under construction at MIT-Bates, with the gun chamber on the left and the preparation chamber on the right.

The high-performance research computing facility at MIT-Bates supports 71 water-cooled racks—each with up to 10 kilowatts of cooling power—for LHC data analysis as well as for the Laser Interferometer Gravitational-Wave Observatory experiment; for ocean and climate modeling by a group in the Department of Earth, Atmospheric, and Planetary Sciences; and for other LNS research uses.

MIT Central Machine Shop

LNS 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 from off-campus sites. The work ranges from small jobs to complex operations that require precision machining, as in a parabolic mirror made from stainless steel for MIT's Alcator C-mod tokamak, or the construction of a high-vacuum chamber for the Research Laboratory for Electronics to investigate new processes in fabrication of organic semiconductor devices.

Figure 4. A stainless steel parabolic mirror for MIT's Alcator C-mod tokamak, made in the Central Machine Shop.

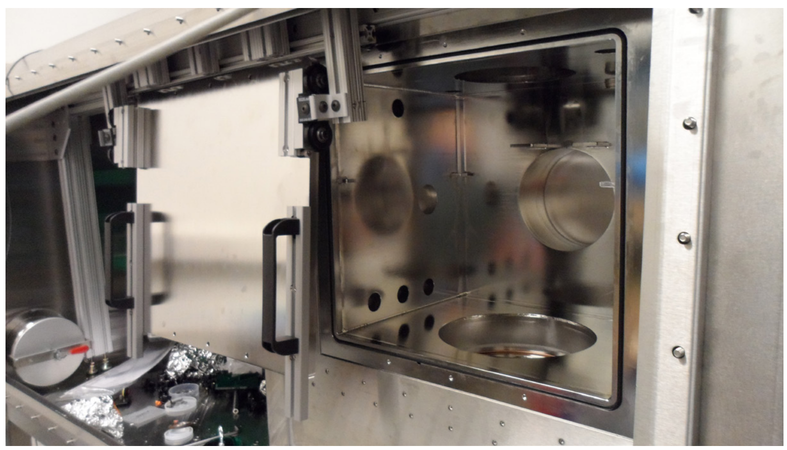

Figure 5. A high vacuum chamber mounted to a glove box, made in the Central Machine shop for the Research Laboratory of Electronics.

Education

Since its founding, LNS has placed education at the forefront of its goals. At present, approximately 70 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 the United States and abroad.

Richard G. Milner
Director
Professor of Physics