# 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 Bates Linear Accelerator Center and the Center for Theoretical Physics. Almost half of the Department of Physics faculty conducts research through LNS. During FY2012, 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 $22.6 million, a decrease of about $2 million from the previous year. Some of the decrease is due to final utilization of federal stimulus funds in FY2011, some to a reduction in DOE funding for nuclear physics in FY2012, and some to a natural reduction in expenses associated with the completion of the Alpha Magnetic Spectrometer. LNS hosted the triennial Particles and Nuclei International Conference in July 2011, a date that marked the centennial of the discovery of the atomic nucleus by Ernest Rutherford.

## Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at 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.

LNS researchers are playing a major role in the Compact Muon Solenoid (CMS) and ATLAS experiments at CERN's Large Hadron Collider. These experiments have begun collecting data that probes the high-energy frontier in physics and will search for new physics beyond the Standard Model. In the CMS experiment, LNS scientists are engaged in data acquisition and distribution systems; in ATLAS, the effort is concentrated mainly on muon detection systems. LNS scientists also are leading the program to study high-energy heavy-ion collisions with the CMS detector. A small effort at the Collider Detector at Fermilab in Batavia, IL, continued until the end of operation of the Tevatron particle accelerator in September 2011.

Both the Collider Detector at Fermilab and the initial Large Hadron Collider efforts are focused on detecting the Higgs particle, which is a key to the puzzle of how particles develop mass. Recently teams from both CMS and ATLAS experiments announced the discovery of a boson with a mass of approximately 125 $GeV/c^2$, in the mass range where the Higgs boson was expected to appear. Additional data will be needed to understand the properties of this boson and compare those measured properties with those expected for the Higgs. Data collection at the Large Hadron Collider continues through early 2013, followed by a major shutdown for a reliability upgrade to achieve the design collision energy of 14 TeV.

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 the DOE's Waste Isolation Pilot Plant near Carlsbad, NM, and is operating there to understand the intrinsic backgrounds of the detector. This detector seeks direct detection of dark matter particles by observing recoiling nuclei from their collisions 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. It will be installed at Waste Isolation Pilot Plant in fall 2012. A larger 1 $m^3$ detector is currently being designed and built, and is expected to be operating 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 nuclear power reactor in France. In December 2011, the Double Chooz experiment presented indications that the remaining unmeasured neutrino mixing angle, $\theta_{13}$, was quite large. The Daya Bay Reactor Neutrino Experiment subsequently confirmed this result with better statistics.

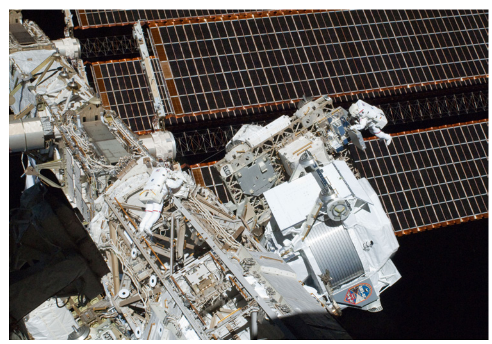

*Figure 1. A view of the Alpha Magnetic Spectrometer (AMS-02) installed on the International Space Station.*

The Alpha Magnetic Spectrometer experiment (AMS-02) is designed to look for cosmic antimatter and evidence for dark matter by operating a large 6717 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 within LNS. The AMS-02 spectrometer was launched on the shuttle *Endeavour*'s last mission, STS-134, to the International Space Station 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 space station. Data collection by the AMS is planned for the next 10–18 years. In the first year of operation, AMS has collected more than 17 billion events. Systematic analysis of the data is under way, led by the Electromagnetic Interactions Group. The group also is responsible for proper operation of the spectrometer, a critical and difficult effort given the space station's hostile thermal environment.

## 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 of 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 the 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.

A new experiment at the DORIS electron/positron storage ring at DESY is being led by LNS researchers to determine fundamental aspects of electron and positron scattering from the proton. The experiment, OLYMPUS, utilizes many elements of the Bates Large Acceptance Spectrometer Toroid, which was used at Bates from 2003–2005 to carry out a program of precision measurements of elastic form factors. A new target system for OLYMPUS was designed and built at Bates, as well as new detectors supplied by LNS and other collaborators. Data collection began January 2012 with a test run, with the data-taking phase of the experiment expected to be completed by the end of 2012.

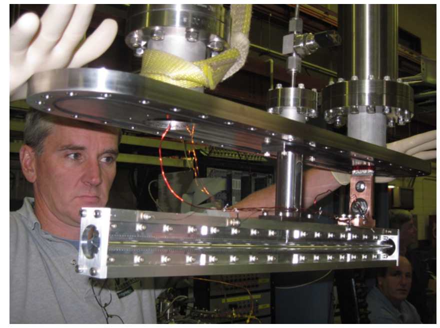

*Figure 2. Bates technician Peter Binns prepares the 60 cm-long OLYMPUS target cell (suspended from the top flange) for insertion into the target chamber.*

The spin structure of the proton is being investigated using the Solenoidal Tracker at RHIC (STAR) detector in polarized proton-proton collisions. A new detector subsystem for STAR, the Forward GEM Tracker, is nearing completion at Bates, with installation of half the detector segments occurring last fall. This system will greatly increase 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, is in progress, with one element, the Intermediate Silicon Tracker, being developed by LNS physicists and Bates engineering staff.

The $Q_{weak}$ experiment at JLab recently completed its data acquisition phase. The $Q_{weak}$ toroidal spectrometer was engineered, constructed, and commissioned at the Bates Research and Engineering Center. The goal of the experiment is a precision measurement of parity-violating electron scattering to measure the weak charge of the proton to challenge predictions of the Standard Model and search for new physics. Another experiment at JLab, PREX, has published results on the neutron radius of lead, with the neutron radius found to be larger than the proton radius by 0.34 fm. This is the first electroweak observation of the expected neutron skin.

A new effort to search for dark matter using the 100 MeV JLab free electron laser 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. Design of the target and detector systems is under way, and a test run in summer 2012 will verify the compatibility of the free electron laser beam with the required narrow aperture (2 mm) target tube.

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 Compact Muon Solenoid experiment heavy-ion program at CERN in physics analysis, experiment operation, and spectrometer improvements. The group will use heavy-ion collision data from the Compact Muon Solenoid experiment 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, including the first-ever study of photon-jet correlations in heavy-ion collisions and the first high-statistics study of dijet properties in heavy-ion collisions.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment in Karlsruhe, Germany, which will make a new precise measurement of the mass of the electron neutrino using the endpoint of the electron energy spectrum from tritium beta decay. Experiment commissioning is taking place in 2012. The LNS Neutrino Group also is developing a novel technique using frequency measurements to measure the electron neutrino mass even more precisely.

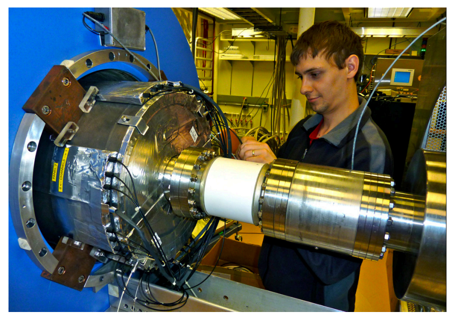

*Figure 3. MIT graduate student John Barrett working on the KATRIN veto system in the focal plane detector during commissioning at the University of Washington.*

## 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 chromodynamics (QCD) calculations of inclusive hadronic jet production cross sections. This plays an important role in establishing exclusion limits for the Higgs search at the Large Hadron Collider 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 the Compact Muon Solenoid and ATLAS detectors in heavy-ion collisions at the Large Hadron Collider; 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 nucleon structure observables with physical pion masses and completion of the first lattice calculation of transverse-momentum-dependent parton distribution functions.

Another important area of nuclear theory research is in electroweak probes and interactions. MIT theorists have used a superscaling approach to successfully describe inclusive electron scattering results, and are now using the same approach to describe neutrino scattering results from Fermilab. Another effort in the area of parity-conserving and -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 the Departments of Mathematics and Electrical Engineering and Computer Science.

## 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.

## Bates Linear Accelerator Center

For three decades, the focus of LNS activities in hadronic physics was the Bates Linear Accelerator Center, operated by LNS for the US DOE as a national user facility. In 2005, 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. 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 Bates, with MIT scientists and engineers developing and designing new accelerators and accelerator-based systems for both fundamental and applied investigation. A compact synchrotron for proton cancer therapy, invented and developed by professor V.E. Balakin from the Lebedev Physical Institute in Russia, and further developed at Bates under a grant from ProTom International, has been installed at the McLaren Health Care Regional Medical Center in Flint, MI. This compact system is estimated to cost about one-third of traditional systems used for proton therapy, thus allowing for much greater use of this important technique. In other accelerator applications, systems for scanning cargo for hazardous materials have been developed with industrial partners under grants from the US Departments of Homeland Security and Defense.

The high-performance research computing facility at Bates supports 71 water-cooled racks, each with up to 10 kW of cooling power, for Large Hadron Collider data analysis; 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 MIT physics research uses.

## Central Machine Shop

LNS operates the 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 more complex ones that require precision machining, as in the small aluminum propellers made for a project in the Department of Media Arts and Sciences, and custom head posts created for research in the McGovern Institute for Brain Research, using magnetic resonance images of monkeys' heads.

*Figure 4.Two aluminum propellers made in the Central Machine Shop.*

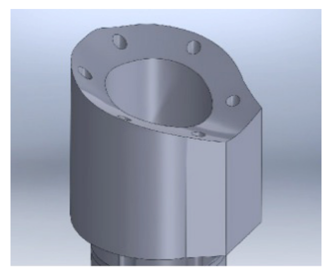

*Figure 5. A CAD drawing created using a magnetic resonance image of a monkey's head, to be used to machine a custom head post.*

## PANIC11

LNS hosted the 19th Particles and Nuclei International Conference in July 2011, with 470 attendees (about half of whom were students and postdocs) from 35 countries. Broad support for this conference was provided by the DOE, the National Science Foundation, national and foreign research laboratories, and MIT. The conference was outstanding, both scientifically and organizationally, and a fitting tribute to the centennial of the discovery of the atomic nucleus by Lord Ernest Rutherford, and the 65th anniversary of the founding of LNS. During the conference, a reception was held at the MIT Museum for MIT alumni conference attendees and friends of LNS to celebrate the anniversary.

## Education

Since its founding, LNS has placed education at the forefront of its goals. At present, approximately 75 graduate students are receiving their training through LNS research programs. A number of undergraduate students also are heavily involved in LNS research. LNS has educated a significant portion of the leaders of nuclear and particle physics in this country and abroad.

## Personnel Transitions

Dr. Karen Dow replaced Stephen Steadman as LNS associate director, who retired from that role but continued half time for the year as scientific administrator. James Kelsey was appointed Bates operations manager to replace Karen Dow. Paul Acosta replaced J. Maynard Gelinas as LNS computer services manager. Ernest Ihloff and James Kelsey were promoted to principal research engineer.

**Richard G. Milner**
**Director**
**Professor of Physics**