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 Linear Accelerator Center and the Center for Theoretical Physics. Almost half the faculty of the Department of Physics conduct research through LNS. During fiscal year 2014, with funding coming from the US Department of Energy (DOE), the National Science Foundation (NSF), the Army Research Office, and other sources, the total research volume was $21.6 million, an increase of about $0.6 million from the previous year. Although sequestration in federal fiscal year 2013 affected the LNS research volume to some extent, and there have been reductions in federal funding in some areas (in theoretical high energy physics, for example), LNS researchers have successfully pursued multiple funding opportunities that have contributed to a slight increase in research volume.

Experimental Particle Physics

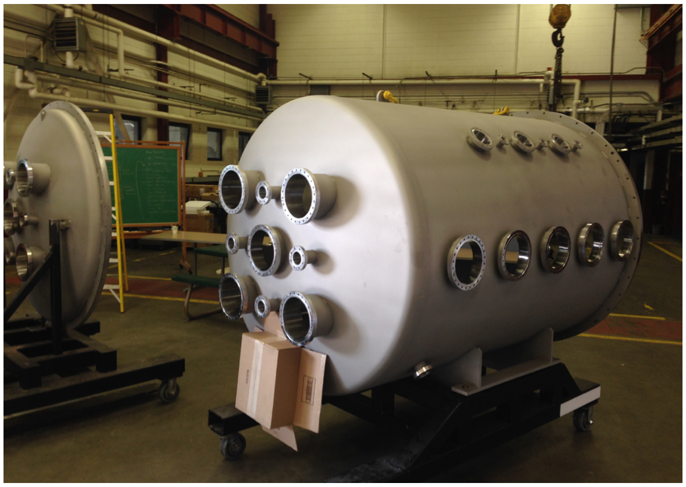
LNS researchers in experimental high-energy particle physics are active at CERN in Geneva, Switzerland. The overall objective of current research in high-energy particle physics is to test as precisely as possible the Standard Model of particles and forces, which has been very successful in describing 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.

The Alpha Magnetic Spectrometer (AMS) experiment (AMS-02) 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 international AMS collaboration consists of more than 500 scientists (primarily particle physicists) led by the Electromagnetic Interactions (EMI) Group within LNS. All systems are functioning as intended and data collection began shortly after the spectrometer's arrival at the ISS in May 2011. Data collection is planned for the next 8–16 years. In the first three years of operation, AMS has collected more than 50 billion events. Systematic analysis of the data is under way, led by the EMI group. In addition to the first AMS result on the positron fraction in cosmic rays, the group is also studying the proton, helium, positron, and electron fluxes, the dependence of the positron fraction on direction, and the boron-to-carbon ratio. These measurements will provide information on solar phenomena and on the origin and propagation of cosmic rays. The group is also responsible for proper operation of the spectrometer, a critical and difficult effort given the hostile thermal environment of the ISS.

LNS researchers are playing a major role in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN. This experiment is collecting data that probes the high-energy frontier in physics and will search for evidence of a new physics beyond the Standard Model. LNS scientists are engaged in 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.

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 (another LHC experiment, with past LNS participation) announced discovery of a boson with a mass of approximately 125 GeV/c2—that is, in the mass range where the Higgs particle 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's Higgs boson. The spin and parity of the boson are consistent with the Standard Model's expectation for the Higgs particle, but many more properties need to be measured. Data collection at the LHC continued through early 2013. The 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. With the increased collision energy and luminosity, the LNS group will also begin a program to search for dark matter with the CMS detector.

Development of new experimental techniques is an important component of LNS research, including the 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 (WIPP) near Carlsbad, NM, and was operated there so researchers could understand the intrinsic backgrounds of the detector. This type of detector seeks direct detection of dark-matter particles by observing nuclei recoiling from 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. An even larger (1 m^3) detector has been designed and built with the help of engineers at the Bates Accelerator/Research and Engineering Center, based on improvements suggested by operating experience with the 10- and 20-liter detectors. The 1 m^3 detector is at MIT undergoing final assembly; it will then be tested and calibrated.



The vacuum chamber for the 1 m^3 Dark Matter Time Projection Chamber detector, with the chamber end cap to the left .

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, was 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 the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND). The first stage of the development is in progress; a beam from a new, very intense ion source is now being characterized in a test cyclotron magnet at Best Cyclotron Systems in Vancouver, Canada. The group is also developing an ion source and beam transport line to perform high-intensity inflection and acceleration tests at a cyclotron in Catania, Italy.

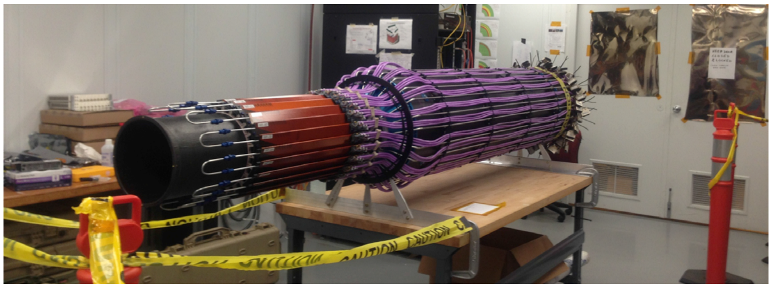
Experimental Nuclear Physics

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

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 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 to achieve 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. 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 2015.

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. Recent analysis led by LNS researchers of data from STAR suggests that the contribution by virtual antiquarks inside the proton toward the spin of the proton is sizable. The Heavy Flavor Tracker (HFT), an upgrade of the STAR detector system, was completed in fall 2013, with one element, the Intermediate Silicon Tracker, developed by LNS physicists and Bates engineering and technical staff. The HFT was used in the 2014 STAR run period and operated smoothly.



Twenty-four staves (orange rectangles, with purple readout cables) of the STAR Intermediate Silicon Tracker assembled on the support cylinder, before insertion into the STAR spectrometer.

The Q_{weak} toroidal spectrometer was engineered, constructed, and commissioned at the Bates Accelerator/Research and Engineering Center. The Q_{weak} experiment at JLab completed its data acquisition phase in May 2012. The goal of the experiment is a precise measurement of parity-violating electron scattering to measure the weak charge of the proton, challenge predictions of the Standard Model, and search for evidence of a new physics. Analysis of the first data set (4% of the total data set) is complete; the initial result was published in October 2013. Analysis of the full data set is in progress.

LNS researchers are participating in the development of a new experiment at JLab, GlueX, to study the light-quark meson spectrum. This includes the design and construction of a Cerenkov detector for particle identification, a software trigger system, and development of analysis techniques.

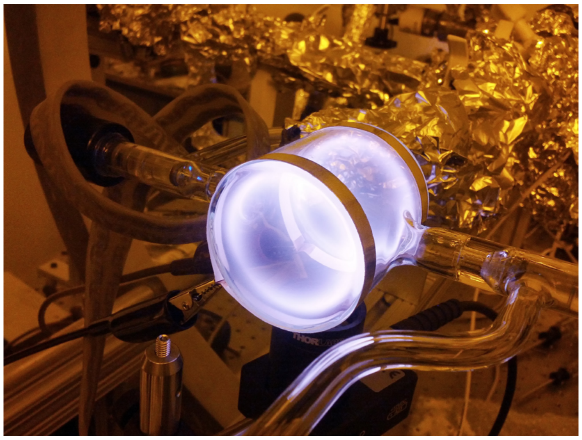
A new effort to search for dark matter using the 100 MeV JLab free electron laser (FEL) has been launched by both experimental and theoretical nuclear and high-energy physicists from LNS. New models suggest that dark matter interacts through a "dark force" carried by a GeV-scale particle. The DarkLight experiment would search for this proposed light boson carrier through its decay to an electron-positron pair. The experiment has received full approval from the JLab Program Advisory Committee. NSF is funding construction of a Phase 1 detector system to be used to develop FEL beam operation techniques with an embedded detector, measure Standard Model processes that are backgrounds for the final experiment, and begin measurements to search for the light boson carrier. Design of the final target and detector systems is proceeding in parallel with development of the Phase 1 system. Funding for detailed design and construction of the final experimental equipment will be sought from the US Department of Energy.

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's heavy-ion program at CERN in physics analysis, experiment operation, and spectrometer improvements. 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 (p-p) collision data sets. These papers include a comparison of the angular distribution of the radiated energy in p-p and Pb-Pb collisions, the first study of dijet properties in p-Pb collisions, the first study of photon-jet correlations in p-p and p-Pb collisions, and the first measurement of fully reconstructed B-mesons in p-Pb collisions. The group is leading an upgrade of the level 1 calorimeter trigger to make effective use of the higher collision rates that will be available in 2015.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment at Karlsruhe, Germany. KATRIN 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. LNS researchers have developed the simulation program for the full experiment, including a Fourier transform on multipoles technique to track particles through electromagnetic fields. Full experiment commissioning is under way. The LNS Neutrino

Group is also developing a novel technique to measure the mass of the electron neutrino even more precisely using frequency measurements.

LNS physicists are developing a source of polarized ^{3}He ions for use in colliding beam experiments to study nucleon structure at RHIC. In a test experiment at MIT, ^{3}He atoms were polarized in a glass cell; they then flowed to a second cell that was located downstream of a solenoidal magnet, where the polarization was again measured, to understand the effects of magnetic field gradients on ^{3}He polarization. A similar system is now being assembled at BNL for use with the Electron Beam Ionization Source, which will ionize the ^{3}He and inject the ions into RHIC.



A plasma discharge in a glass cell containing ^{3}He.

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 structures 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 described below.

MIT theorists have performed a high-precision calculation for Higgs particle production with a jet veto, and have derived factorization theorems for exclusive jets produced in deep inelastic scattering. These calculations allow the CMS and ATLAS collaborations to extract information on Higgs properties from the experimental data.

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 the LHC; these jets lose energy without a significant change in their angular or momentum distributions.

Lattice quantum chromodynamics (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 agreement of calculations with experimental results for the isovector nucleon electric and magnetic form factors in the first Lattice QCD calculation to use a nearly physical pion mass.

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 for understanding current experimental results and for planning experiments at a possible future electron-ion collider.

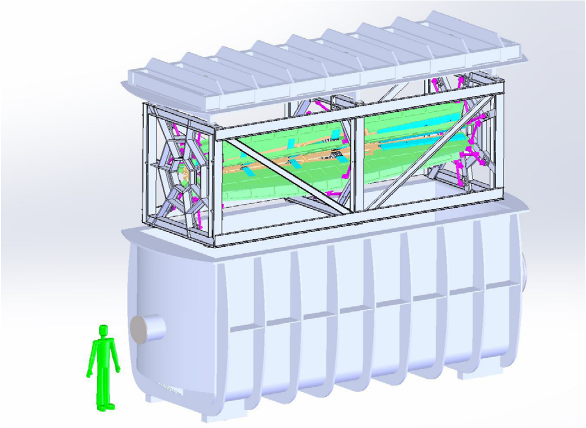
Particle theorists are active in a wide range of areas, from field theory, supergravity computations, and jet quenching to string theory, dark energy, neutrino masses, quantum computation, and quantum information. They work in collaboration with experimentalists as well as colleagues in condensed matter 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 of 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 DOE as a national user facility. In 2005, the center 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 research on the



An engineering model of the complex hybrid toroidal magnet, support structure, and surrounding vacuum chamber for the MOLLER experiment. The magnet coils (green), support structure (silver beams and magenta alignment struts), and top vacuum flange are lifted out of the vacuum chamber in this view.

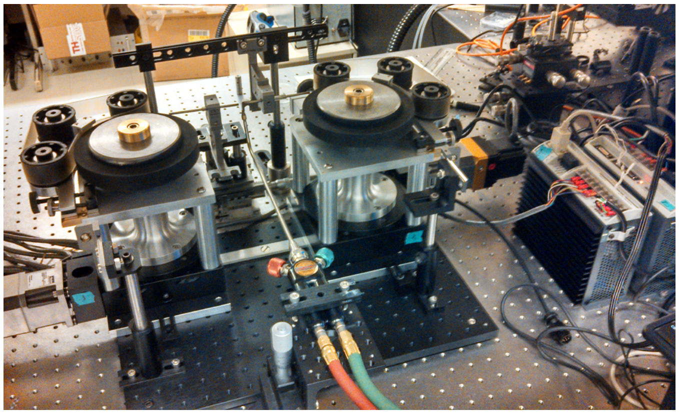
frontier of physics. For example, MIT-Bates Center engineers have begun to design a complex hybrid toroidal magnet, support structure, and surrounding vacuum chamber for the MOLLER experiment at Jefferson Lab. Furthermore, MIT-Bates Center physicists, engineers, and technicians have made contributions 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 compact synchrotron for proton cancer therapy, invented and developed by Professor V. E. Balakin of the Lebedev Physics Institute in Russia and further developed at the MIT-Bates Center under a grant from ProTom International, has received US Food and Drug Administration approval for use in treating patients. MIT-Bates Center physicists, engineers, and technicians have built a high-intensity, polarized electron source with the goal of improving on the average currents now possible 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.

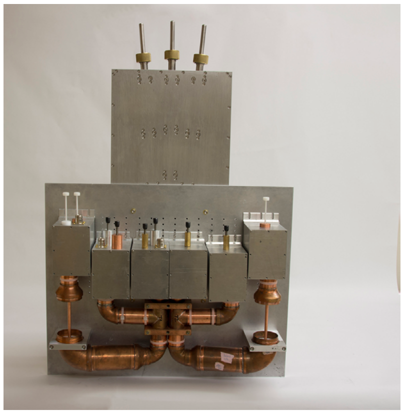
The high-performance research computing facility at the MIT-Bates Center supports 71 water-cooled racks, each with up to 10 kW of cooling power. These are useful for LHC data analysis, for the Laser Interferometer Gravitational-Wave Observatory experiment, for ocean and climate modeling, for computational fluid dynamics relative to ship hull design, and for other LNS research uses.

MIT Central Machine Shop

LNS also operates the MIT Central Machine Shop as a service center. The Central Machine Shop is used across MIT to build research-related equipment, as well as



A fiber optics tapering device for MIT's Institute for Soldier Nanotechnologies, made in the Central Machine Shop. A fiber optic cable is held between two rubber-faced wheels and belts that rotate slowly. The cable is heated, and one wheel rotates faster than the other, stretching the cable.



The underside of the bottom of a solid-state nuclear magnetic resonance probe made in the Central Machine Shop for the Plasma Science and Fusion Center, showing a high-power radio-frequency circuit and tuning elements.

performing work for the Department of Facilities and for research facilities at off-campus sites. The work ranges from small jobs to complex jobs that require precision machining, as in a fiber optics tapering device for the Institute for Soldier Nanotechnologies and development of a magic-angle-spinning solid-state nuclear magnetic resonance probe for the Plasma Science and Fusion Center.

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