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 Department of Physics faculty conduct research through LNS.

During FY2018, total research volume with funding provided by the US Department of Energy (DOE), the National Science Foundation (NSF), and other sources was $21.1 million, a decrease of about $0.8 million from the previous year. This decrease was due primarily to a reduction in federal funding in certain areas (medium-energy nuclear physics, for example). Some LNS faculty members have successfully pursued foundation funding to compensate; foundation funding typically runs through the Department of Physics and therefore does not appear as LNS research volume. In addition, LNS researchers are successfully pursuing multiple funding opportunities that should maintain or even increase research volume in the future. Six LNS junior faculty currently hold prestigious Early Career/CAREER Awards from DOE and NSF.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at CERN in Geneva, Switzerland; the Fermi National Accelerator Laboratory (Fermilab) in Illinois; and 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 by either searching directly for new phenomena or measuring predicted quantities as precisely as possible and thus testing the Standard Model, which has been very successful in describing a wide variety of phenomena. 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 CERN Large Hadron Collider (LHC) in the areas of data acquisition, massive computing, detector upgrades, and data analysis. LNS scientists also are leading the program to study high-energy heavy-ion collisions with the CMS. The LHC has accumulated a significant data sample at the present energy frontier (13 TeV center-of-mass energy) and will, by the end of the second run (2015–2018), collect a sample of over 120 fb^{-1} at an energy almost twice as high as that in the first run (2010–2012). A new faculty member, Professor Philip Harris, is working on improvements to the CMS triggering system that selects events of interest to cope with the higher event rates at these higher energies and beam intensities. A collision of interest would appear with an additional 200 overlapping events, and the initial trigger decision must be made within 10 microseconds. The first improvement involves a special algorithm on a chip to perform high-speed pattern reconstruction. Then, for each selected event, machine learning algorithms will be used on detector information to reconstruct detailed event parameters and determine whether the event is of physics interest.

After the discovery of the Higgs boson in the first run, LNS researchers are using the CMS to search for dark matter and to measure detailed properties of the boson.

The CMS dark matter searches have so far revealed no sign of dark matter in the channels examined. Other LNS researchers are working on GAPS (General Antiparticle Spectrometer), an astroparticle experiment 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 be a signal of new physics and would lead to a probe of a variety of dark matter models.

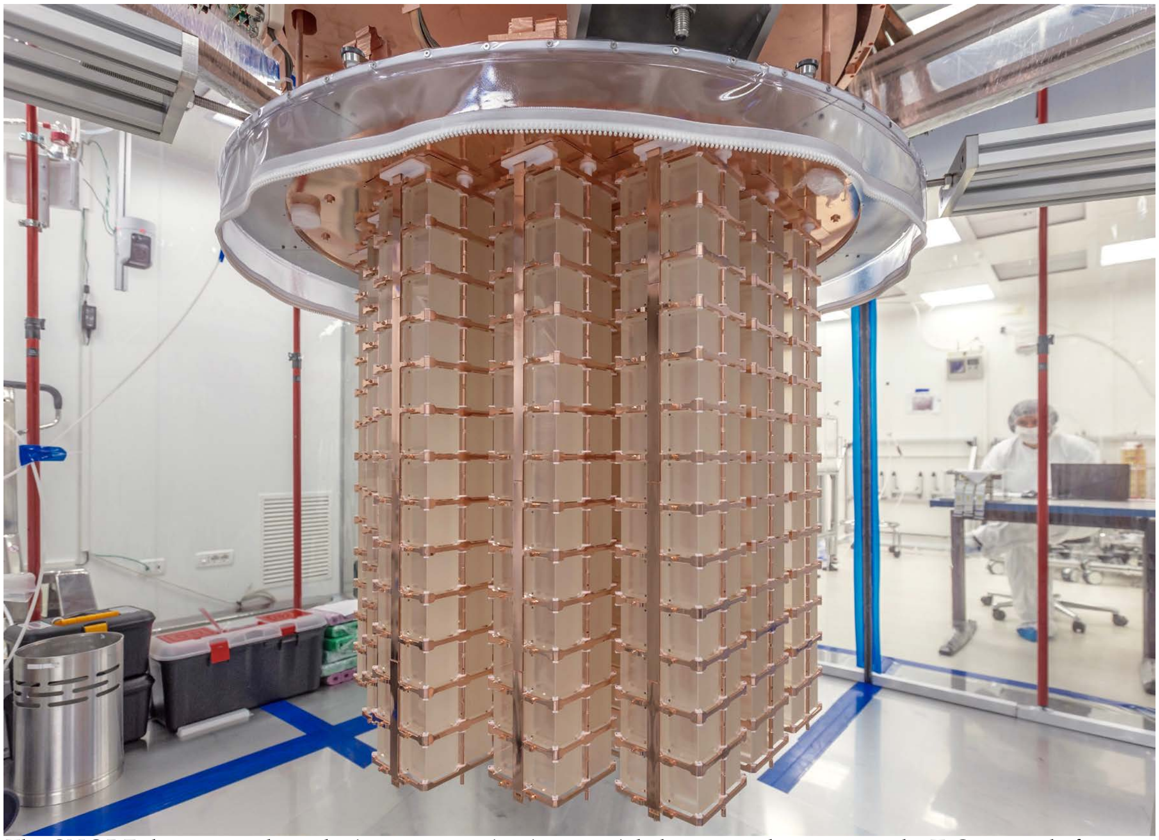
The Alpha Magnetic Spectrometer experiment (AMS-02), led by the Electromagnetic Interactions (EMI) group in LNS, is designed to look for cosmic antimatter and evidence of dark matter by operating a large 6,717-kg magnetic spectrometer above Earth's atmosphere on the International Space Station (ISS). AMS has been collecting data since 2011 and now has collected information on more than 120 billion cosmic ray events, far more than in the entire history of cosmic ray physics. 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 comparisons of the lithium, beryllium, and boron flux in cosmic rays. These three nuclei are considered secondary cosmic rays, as they are thought to be produced by the collision of primary cosmic rays (carbon, helium, and oxygen) with the interstellar medium. The AMS results are much more precise than previous measurements and involve a wider range of rigidity. The fluxes of these three secondary cosmic rays have a similar rigidity dependence above about 30 GV; this dependence is quite different from that for the fluxes of the three primary cosmic rays (which are themselves quite similar in rigidity dependence). More theoretical work is needed to understand these similarities and differences. Data will continue to be collected on electrons, positrons, protons, antiprotons, helium, and other nuclei and anti-nuclei until the end of ISS operations, presently scheduled for 2024.

LNS researchers are studying the fundamental properties of neutrinos via the Booster Neutrino Experiment and related experiments at the Fermilab. In addition, they are participating in the IceCube collaboration to search for sterile neutrinos in an experiment at the South Pole. They also continue to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos and are in the process of constructing a high-intensity ion source to feed the future synchrotron.

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.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, seeking to measure the neutrino's mass and understand whether the neutrino is its own antiparticle (i.e., a Majorana particle). MIT physicists are part of the CUORE collaboration in Gran Sasso, Italy, and the KAMLAND-Zen collaboration at the Kamioka Observatory in Japan, searching for neutrinoless double beta decay (NDBD). If observed, this would imply that the neutrino is its own antiparticle. Part of this search involves the establishment of novel detector techniques, including the use of quantum dots and development of scintillating bolometer detectors. MIT physicists are also playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment in Karlsruhe, Germany, as well as the Project 8 experiment; both of these experiments intend to provide precise new measurements of the mass of the electron neutrino using the endpoint of the electron energy spectrum from tritium beta decay.



The CUORE detector package during construction in a special cleanroom that protects the TeO_2 crystals from contamination caused by naturally occurring radioactivity such as radon gas. Each crystal is a cube 5 cm on a side; a ladder of 13 layers of four crystals each is approximately 80 cm tall. From Professor Lindley Winslow.

CUORE consists of 988 TeO_2 bolometers operating at 10 mK, with the primary physics goal of searching for NDBD of ^{130}Te. The detector is considered the coldest cubic meter in the universe. CUORE collected its first data set with the full detector in the summer of 2017, and the measured background was consistent with expectations. No NDBD events were seen with the NDBD half-life of ^{130}Te set to the most stringent limit to date. The 2017 data also resulted in the most precise measurement of the two-neutrino double beta decay half-life of ^{130}Te. MIT collaborators participated in the data collection and analysis, leading the background modeling effort.

KATRIN commissioning continues with a first measurement of the energy spectrum from tritium beta decay. The expectation is that the experiment will achieve design sensitivity with about three beam years of operation. Project 8 is developing a novel technique to measure the electron neutrino mass even more precisely than KATRIN, using frequency measurements. A new measurement cell has been built and commissioned using a radioactive isotope of krypton. 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.

LNS researchers are prominent in relativistic heavy-ion physics. The Heavy Ion group plays leading roles in the CMS heavy-ion program and the sPHENIX collaboration at the Brookhaven National Laboratory in New York. Physics results in FY2018 include high-precision measurements of dijet pseudorapidity distributions, providing the most detailed information on Parton distribution function (PDF) nuclear effects at the LHC to date. This is the first evidence that the gluon PDF in lead ions is strongly suppressed with respect to the PDF in unbound nucleons. At Brookhaven, sPHENIX will be used to study jet quenching in heavy-ion collisions in a complementary fashion to CMS. MIT contributions are in the areas of collaboration leadership and design, implementation, and optimization of particle tracking software.

LNS nuclear physics researchers are leading several important efforts at accelerator facilities in the United States and Europe, including the Relativistic Heavy Ion Collider (RHIC), the Thomas Jefferson National Accelerator Facility (JLab), the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, and the LHC experiment at CERN. The main thrust of these experiments is a detailed understanding of the properties of protons, neutrons, and light nuclei. Two of the experiments are in the development and commissioning stages (GlueX at JLab, nEDM at SNS).

Results of the Q_{weak} experiment, which ran at JLab and included a precision measurement of the weak charge of protons, were published in *Nature* in May 2018. The measurement was in excellent agreement with the electroweak model of physics.

An experiment designed to measure the radiative Møller scattering process has run at MIT's High Voltage Research Laboratory (HVRL) using the 3 MeV electron beam there. A number of improvements have been made to the HVRL Van de Graaff instrument to tune and measure its beam properties. This process is an important background for the DarkLight experiment and has never been measured experimentally.

A new faculty member, Professor Or Hen, works in the area of short-range correlations, a vibrant field of research with implications for astrophysics, particle physics, and nuclear physics. Experiments at JLab have explored hard knockout reactions using semi-inclusive and exclusive electron scattering, measuring both the scattered electron and a proton or neutron knocked out of the target nucleus. Analysis of (e,e′n) and (e,e′p) scattering off a range of nuclei shows that at low momentum the nucleon knockout is dominated by simple nucleon counting, whereas at high momentum the knockout is dominated by short-range-correlated neutron-proton pairs. Also, as neutrons are added to the nucleus, the pairing probability of neutrons saturates while that of protons grows.

Theoretical Particle and Nuclear Physics

Research at the Center for Theoretical Physics seeks to extend and unify our understanding of fundamental physics. CTP celebrated its 50th anniversary in March 2018 with a daylong symposium featuring talks by former CTP students, postdocs, and faculty as well as some current faculty.

A panel of faculty members discussed the future of theoretical physics during the symposium celebrating the 50th anniversary of the MIT Center for Theoretical Physics. (Left to right: Professors Jesse Thaler, Will Detmold, Daniel Harlow, Tracy Slatyer, and Aram Harrow) From James Kelsey.

During the past year's hiring cycle CTP hired two outstanding new young faculty members. Phiala Shanahan will start as an assistant professor in July 2018; she uses lattice QCD (quantum chromodynamic force) and other approaches to study strongly interacting quantum systems and is pioneering the use of machine learning methodology to dramatically increase the effectiveness of these computational methods. Netta Engelhardt, a general relativist who has developed a new framework for understanding black hole horizons and related puzzles, will join CTP in 2019. These two hires have doubled the number of women faculty hired into CTP over the last 50 years.

Although 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 through existing experiments, this model describes only 5% of the mass-energy in the observed universe. Also, it does not explain how gravity fits into the framework of quantum physics that underlies the model, it does not explain cosmology or the very early universe, and it contains roughly 19 independent numerical parameters and a set of forces and particles that as yet cannot be explained via 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. In addition, 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 CTP are working at the forefront of research on all of these questions and others, including related problems that connect to mathematics, condensed matter physics, astrophysics, and quantum information. CTP is unusual among university groups in both its breadth and unity. A few examples of recent work are described below.

The nuclear theory group within CTP focuses on trying to understand the structure and interactions of nuclei composed of quarks that interact through QCD. The lattice QCD

(LQCD) effort, led by junior faculty member William Detmold, focuses on calculating the properties and interactions of light nuclei. At MIT, this computational approach has led to the first calculations of the proton-proton fusion process (relevant for energy production in the sun) and the weak decay of tritium, as well as the simplest nuclear transition that contributes to double beta decay. Over the last year, Detmold and his group have continued to study nuclei and their properties and reactions, extending the size of the nucleus for which calculations can be performed. Also, Detmold and Shanahan have been investigating new ways of performing LQCD calculations faster using machine learning and custom hardware. Professor Krishna Rajagopal's research focuses on how quarks behave in extraordinary conditions such as the hot quark soup that filled the microseconds-old universe. He has recently proposed new signatures for the experimental detection of a possible critical point in the phase diagram of this liquid, motivating a campaign of measurements at the RHIC that will begin next year.

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, colleagues in condensed matter theory, and fellow faculty members in the Department of Mathematics and the Department of Electrical Engineering and Computer Science. A current focal area of theoretical research, particularly for junior faculty member Tracy Slatyer and recently tenured Jesse Thaler, is the 80% of matter in the universe that is "dark" and not described by the Standard Model. Slatyer is building a comprehensive new set of tools for predicting the signatures of dark matter physics in the early history of our universe; in the past year, she has used these tools to map out the possible effects of dark matter annihilation, decay, and scattering on radiation signals from the epoch when the first stars were formed. Simultaneously, she and Professor Iain Stewart have presented the first high-precision predictions of the gamma-ray signal that could be detected if dark matter is heavy and interacts through the weak nuclear force; this knowledge will substantially improve the capability of gamma-ray telescopes to test such dark matter scenarios. Recently Thaler has used advanced statistical techniques to expose new features of QCD, and he is using this knowledge to construct novel machine learning architectures to probe the collision debris at the LHC. He has also proposed new strategies to hunt for dark matter, including the conceptual design for the MIT-led ABRACADABRA experiment and a forthcoming laser cavity design based on technology developed for the Laser Interferometer Gravitational-Wave Observatory (LIGO).

The CTP string and quantum gravity group has made new progress in several directions. New assistant professor Daniel Harlow, working with Harvard faculty member Daniel Jafferis, has identified connections between the factorization structure of the quantum Hilbert space and the existence of a holographic description in simple models of quantum gravity that may illuminate current efforts in understanding black holes and quantum gravity. Professor Washington Taylor and his group have identified constraints from string theory on how matter fields can be charged under gauge forces, showing specific ways in which string theory imposes constraints not apparent in quantum field theory. Professor Barton Zwiebach, working with Brandeis professor Matthew Headrick (a former MIT Pappalardo Fellow), has computed previously unknown minimal area metrics on certain surfaces that describe "Feynman diagrams" of string field theory.

Other work in CTP focuses on quantum systems, quantum information, and quantum computing. Professors Alan Guth and David Kaiser (joint appointment in CTP and the Program in Science, Technology, and Society) will soon publish a paper in *Physical Review Letters* on their Cosmic Bell experiment; this experiment, by exploring the quantum behavior of pairs of photons from stars that lie in different directions in the sky, addresses the fundamental question of whether what Einstein referred to as the "spooky action at a distance" of quantum physics can be shown not to depend on hidden correlations. The paper will show that such correlations cannot come from anywhere within a window extending over seven light-years away. The work of Professor Hong Liu on non-equilibrium effective quantum field theory has led to new signatures for many-body chaos. Professor Frank Wilczek, with former MIT student Jordan Cotler, has proposed a new way of using quantum entanglement to allow interference between light of different wavelengths that is being demonstrated and tested experimentally in ongoing experiments in Japan and China.

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. Recently tenured associate professor Aram Harrow carries out forefront work in these areas. In the last year, Harrow has been investigating how a quantum computer can be useful for machine learning, even in the case of data sets that are far too large to fit on the computer. This is especially relevant as the first fairly small-scale quantum computers come online. This work also establishes the first rigorous speed-ups for machine learning problems in a realistic setting. The work of Professor Harlow makes strong connections between quantum information questions and quantum gravity as well; he has shown in particular that ideas from quantum error correction seem to play a fundamental role in the holographic framework of quantum gravity.

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 Accelerator Center

DOE provides base support for a research and engineering center where US nuclear physicists, including LNS faculty and their collaborators, develop new instrumentation for frontier research. Funding for specific projects also comes from DOE, NSF, other universities and laboratories, and industry. For example, MIT Bates engineers and technicians have designed and will test a prototype coil for a hybrid toroid magnet for the future Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) experiment at the Jefferson Lab. The aim of the experiment is to detect scattered electrons at very forward angles, so the coil profile is long in the beam direction (almost 7 m long) and narrow in the azimuthal direction (over 0.3 m wide), allowing the electrons to be bent far enough from the beam line to be detected.

The prototype coil for the MOLLER experiment hybrid toroid on its winding frame, mounted on a steel support beam for shipping. From Scott Morley.

MIT Bates physicists, engineers, and technicians have also made contributions to many of the experiments discussed above.

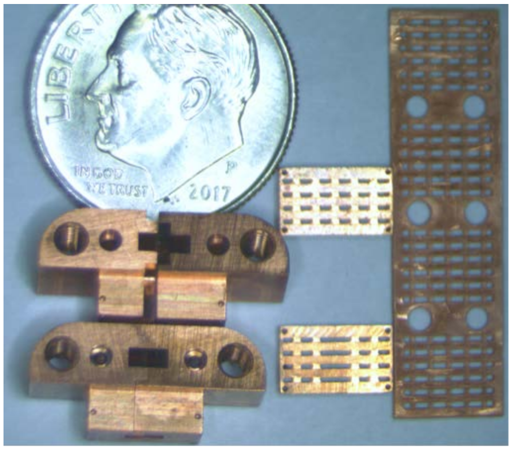
In addition, research using particle accelerators is a major focus at MIT Bates, with Institute scientists and engineers developing and designing new accelerators and accelerator-based systems for both fundamental and applied investigations. Bates physicists, engineers, and technicians have built a high-intensity polarized electron source with the goal of improving on the average currents possible with existing sources by one to two orders of magnitude. The source has already reached 5 mA of current, a new world record. Such a source is essential for some versions of a future electron-ion collider; the US Nuclear Science Advisory Committee has deemed this type of collider as the next major nuclear physics facility to be built.

The high-performance research computing facility at Bates supports 70 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power for LHC data analysis, LQCD calculations, ocean and climate modeling, and other LNS research uses.

Professor Robert Redwine stepped down as director of MIT Bates on June 30, 2018, after 12 years of service in that role, leading Bates through the final stages of transition from a single-purpose DOE national user facility to a research and engineering center working on many DOE and MIT projects. Professor Boleslaw Wyslouch is serving as Bates director as well as LNS director.

MIT Central Machine Shop

LNS operates the MIT Central Machine Shop as a service center. The 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. One such project involves devices for microwave source development research in MIT's Plasma Science and Fusion Center. These devices, operating at frequencies on the order of 100 GHz, require feature dimensions below 0.25 mm with tolerances below 0.005 mm.



Components of a 94 GHz square lattice, photonic bandgap kystron.

From Andrew Gallant.

Another project focuses on machining components for a biomass torrefaction reactor being developed by researchers in the Department of Mechanical Engineering. The reactor is intended to take biomass waste from small farms and heat it in an oxygen-free environment so that it rapidly decomposes and releases low-energy molecules, resulting in compact waste with high energy density. This project is being conducted at MIT Bates.

A prototype biomass torrefaction reactor. Biomass waste is fed into the system through the hopper above the large cylinder in the smaller rectangular enclosure at right and heated inside two pipes toward the bottom of the larger rectangular enclosure in an oxygen-free environment. The enclosure is approximately 2 m tall.

From Andrew Gallant.

Education

Since its founding, LNS has placed education at the forefront of its goals. During the past year, nearly 90 graduate students received 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 in nuclear and particle physics both in the United States and abroad.

Boleslaw Wyslouch
Director
Professor of Physics