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. Almost half of the Department of Physics faculty conduct research through LNS. Fiscal year 2021 saw continued operation with a reduced campus presence due to the Covid-19 pandemic.

Essential research services at the Lab for Nuclear Science focused on keeping computer services running and remotely accessible, and on laboratory research that required hands-on work. Prior planning and hard work by several computing professionals and technicians maintained access to financial systems, research compute servers, and the computers in the MIT-Bates High Performance Research Computing Facility. This enabled LNS researchers to continue to analyze and simulate experimental data, develop theoretical models, and design new detector systems. LNS headquarters personnel were able to carry out their administrative, personnel, and financial activities while working remotely. In-person laboratory research ramped up throughout the year and was consistent with MIT's phased Research Ramp-up program. The MIT Central Machine Shop operated at half-capacity early in the year, then went to full staff when allowed by MIT's rules for core facilities.

During FY2021, total research volume using funding provided by the US Department of Energy (DOE), the National Science Foundation (NSF), and other sources was $23.2 million, an increase of about $3.3 million from the previous year. A sizable portion of this increase is due to the creation of the new NSF Institute for Artificial Intelligence and Fundamental Interactions and new grants to young faculty members; existing research continues to be of interest to funding agencies and ranks highly during competitive reviews. These increases are somewhat offset by a reduction in travel and delays in hiring due to the Covid-19 pandemic. Some LNS faculty have successfully pursued foundation funding. Such funding typically runs through the Department of Physics and therefore does not appear as LNS research volume. Five LNS junior faculty received prestigious Early Career/CAREER Awards from DOE and NSF in FY2021; two of them—Tracy Slatyer and Yen-Jie Lee—were designated as recipients of the Presidential Early Career Awards for Scientists and Engineers. One LNS faculty member, Kerstin Perez, received tenure in the past year.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland; at the Fermi National Accelerator Laboratory (Fermilab) in Illinois; and at 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 by 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 playing principal roles in much of this research.

The Alpha Magnetic Spectrometer (AMS) experiment, led by the Electromagnetic Interactions (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 over 175 billion cosmic ray events—far more than what has been collected 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 effort given the hostile thermal environment of the ISS. In FY2021, they commissioned a major upgrade to the AMS tracker cooling system, installed by ISS astronauts in early 2020. Many improvements have been made to the data analysis, including improved tracker resolution (especially for heavier particles), better knowledge of the absolute rigidity, improved resolution in the rigidity measurement, improved particle charge sign identification and measurement of particle charge, improved energy reconstruction for positrons and electrons, and improved rejection of protons/antiprotons in the electron/positron sample. Results have been published this year on properties of iron primary and fluorine secondary cosmic rays and properties of sodium, aluminum, and nitrogen cosmic rays. Data will continue to be collected on electrons, positrons, protons, antiprotons, helium, and other nuclei and antinuclei until the end of ISS, presently scheduled for 2028.

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, massive computing system, detector upgrades, and data analysis. LNS scientists also are leading the program to study high-energy heavy-ion collisions with the CMS, as discussed below. The LHC has accumulated a significant data sample at the present energy frontier (13 TeV center-of-mass energy). Run 2 (2015–2018) collected a sample of over 120 fb^{-1}, a factor of about five more data, at an energy almost twice as high, compared to Run 1 (2010–2012). While the LHC is now in a long shutdown for repairs and upgrades to the accelerator and detectors, physicists are analyzing this wealth of data. Operations are expected to resume in 2022, delayed by the Covid-19 pandemic.

With the discovery of the Higgs boson accomplished in Run 1, LNS researchers are using CMS to search for dark matter using the signature of missing energy in the detectors, and to measure detailed properties of the Higgs boson to search for physics beyond the Standard Model. The CMS dark matter searches have so far found no sign of dark matter in the channels examined. LNS researchers are also preparing for the higher data rates expected in future LHC runs in the areas of an improved hardware trigger that uses machine learning and improved data transfer and storage.

Other LNS researchers are working on the General Antiparticle Spectrometer (GAPS), an astroparticle experiment that plans to fly on a long-duration Antarctic balloon flight in 2022 (delayed from 2021 due to Covid-19) to search for antideuterons in low energy cosmic rays. MIT is responsible for construction of the semiconducting silicon detectors. If cosmic antideuterons are detected, this would be a signal of new physics and would probe a variety of dark matter models. The Covid-19 pandemic forced a shift in construction site from Columbia University to MIT due to travel restrictions; fortunately, suitable space was available at MIT-Bates. The same researchers use data from the NuSTAR X-ray satellite observatory to search for signatures of light dark matter, including sterile neutrinos and axions.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment and related experiments at Fermilab. This research group also continues to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos, and is testing a high-intensity ion source to feed the future synchrotron. The group participates in the IceCube collaboration to search for sterile neutrinos in an experiment at the South Pole.

Experimental Nuclear Physics

LNS programs span the full breadth of the field of nuclear physics, with research in heavy-ion physics, hadronic physics, fundamental symmetries, and low-energy nuclear structure.

The low-energy nuclear structure program uses precision laser spectroscopy of radioactive molecules at CERN, and soon at the Facility for Rare Isotope Beams at Michigan State University, to study nuclear charge radii, magnetic dipole moments and electrostatic quadrupole moments, leading to information on how neutrons and protons are organized inside the nucleus. These measurements can lead to an understanding of fundamental symmetry violations that may explain why there is so little antimatter in the universe. Renovations of a lab space in Building 24 were completed in the fall of 2020 to support development of these laser spectroscopy techniques

The new clean room in 24-035 built to house both low-power and high-power lasers for developing precision laser spectroscopy techniques to study radioactive molecules. Photo: Ronald Garcia Ruiz

The Heavy Ion Group plays leading roles in the CMS experiment heavy-ion program at CERN and the sPHENIX collaboration at Brookhaven National Laboratory (BNL) in New York. Physics results in FY2021 include the first measurement of hadron spectra in PbPb collisions tagged with the outgoing Z-boson, with the response showing sensitivity to the medium seen by the hadrons, and the first measurement of two-particle correlation functions in e^+e^- collisions, with no anisotropic collective behavior observed. At BNL, sPHENIX will be used to study jet quenching in heavy-ion collisions in a complementary fashion to CMS. sPHENIX equipment is under construction. MIT physicist contributions are in the areas of collaboration leadership and in design, implementation, and optimization of particle tracking software.

LNS medium energy nuclear physics researchers are leading several important efforts at accelerator facilities in the United States and Europe. These facilities include the Relativistic Heavy Ion Collider at BNL, the Jefferson Lab, the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee, the Mainz and DESY (Deutsches Elektronen-Synchrotron) laboratories in Germany, the LHCb (Large Hadron Collider beauty) experiment at CERN, and the Joint Institute for Nuclear Research in Russia. The main thrust of these experiments is a detailed understanding of the properties of the proton, the neutron, and light nuclei. Important results include the first measurement of the charge-averaged lepton-proton elastic scattering cross section and development of a contact formalism to describe how nucleons pair when they're close together independent of the size of the nucleus.

Many LNS researchers have been active in the last year in working out the physics requirements for the detectors for the Electron Ion Collider (EIC). The EIC is the next-generation accelerator facility to study the fundamental structure of matte rand will be built at BNL. Members of LNS working in medium energy nuclear physics, heavy-ion physics, theoretical nuclear physics, along with technical staff from MIT-Bates, expect to be involved in design and construction of the accelerator and experimental equipment and the development of EIC experiments.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, seeking to measure the neutrino mass and to understand whether the neutrino is its own antiparticle (i.e., a Majorana particle). MIT physicists are 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 (NDBD). If observed, this would imply the neutrino is its own antiparticle. Analysis of CUORE data to date sets a new lower limit of 2.2×10^{25} years for the NDBD lifetime in ^{130}Te. Work is proceeding on a possible upgrade to CUORE known as CUPID, which will enable an even more sensitive search for NDBD. MIT physicists are also playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment in Karlsruhe, Germany, and in the Project 8 experiment, both of which intend 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 and Project 8 are both now running using molecular tritium. KATRIN has produced an initial result that indicates the neutrino mass is less than 0.8 eV/c^2 at 90% confidence level; this is the first measurement ever below 1 eV/c^2. The target goal is a mass scale of 0.2 eV/c^2.

Theoretical Particle and Nuclear Physics

Research at the Center for Theoretical Physics (CTP) seeks to extend and unify our understanding of fundamental physics through activities spanning many research areas.

The Standard Model of particle physics provides a powerful theoretical framework for describing most aspects of fundamental physics that can easily be accessed with existing experiments. This model was completed with the discovery of the Higgs boson, which opened up a new era of questions associated with its nature and the study of its interactions with other matter. However, the Standard Model describes only 5% of the mass-energy in the observed universe, does not explain how gravity fits into the framework of quantum physics that underlies the Standard Model, does not explain cosmology or the very early universe, and contains roughly 19 independent numerical parameters and a set of forces and particles that as yet cannot be explained by any more fundamental theory. Within the Standard Model there are also major practical and conceptual challenges in calculating even some simple quantitative features such as the mass of the proton, which is a bound state of quarks, due to the strong coupling of the strong nuclear force. Additionally, 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 the CTP are working at the forefront of research on all these questions and others, including related problems that connect to mathematics, condensed matter physics, astrophysics, and quantum information. The CTP is unusual among university groups in both its breadth and unity. A few examples of recent work are mentioned below.

The nuclear theory group within the CTP focuses on understanding the strong force, described by quantum chromodynamics (QCD). QCD is one of the richest fundamental forces of nature, and the focus of the MIT group includes topics such as understanding the structure and interactions of the proton and larger nuclei, using methods of effective field theory to understand the formation of jets of hadrons when strongly interacting particles are collided at high energies, and exploiting techniques for handling strongly interacting field theories to understand the strongly coupled quark-gluon plasma discovered in heavy-ion collisions. Faculty members William Detmold and Phiala Shanahan lead an effort on lattice QCD, developing theory and algorithms to carry out large scale numerical simulations which focus on calculating key properties and interactions of nucleons and light nuclei. This past year, Shanahan and Detmold have continued efforts to calculate hadronic structure by determining the longitudinal momentum fractions carried by quarks in a ^{3}He nuclear, providing a path towards a QCD understanding of the famous EMC effect. They also showed for the first time that the quenching of the axial charge of a nucleus can be determined from lattice QCD, finding agreement with the experimentally observed reduction of the triton Gamow-Teller decay rate. They authored a review of lattice QCD calculations of nuclear matrix elements.

Krishna Rajagopal's research focuses on how quarks behave in extraordinary conditions such as in the hot quark soup that filled the microseconds-old universe, including using jets to study the microscopic structure of the Quark Gluon Plasma (QGP). He and his collaborators have explored how to improve the hybrid model description of the particles originating from the wake that a jet produced in a heavy-ion collision leaves in the droplet of QGP through which it propagates using linearized hydrodynamics. They are currently focusing on improving their treatment of the interplay between the dynamics of the wake and the expansion of the droplet, which turns out to be key to describing observables that are influenced by soft particles in jets.

Iain Stewart's research involves developing new quantum field theory methods to study the behavior of strongly interacting particles in high energy collisions over a large range of dynamical scales. In the realm of testing the Standard Model, Stewart carried out the first model independent analysis of the inclusive b-quark to s-quark gamma decay that fully incorporates the b-quark distribution function, finding that earlier estimates had underestimated uncertainties, thus leaving more room for physics beyond the Standard Model. Detmold and Stewart are also co-authors on the EIC Yellow Book Report, building the science case for this future collider.

CTP high-energy theorists are active in a wide range of areas that include 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 as well as colleagues in condensed matter theory in the Departments of Mathematics and Electrical Engineering and Computer Science. One focus area of theoretical research, particularly for faculty members Tracy Slatyer, Jesse Thaler, and Frank Wilczek, is that 80% of matter in the universe is gravitationally interacting dark matter that is not described by the Standard Model. During the past year, Slatyer worked out new and precise forecast constraints on heavy weakly-interacting dark matter for the next-generation gamma-ray telescope CTA, showing CTA has the potential to probe the difficult-to-reach thermal higgsino target. Jesse Thaler is developing new techniques to maximize the ability of high energy colliders to discover signals of new heavy particles or fundamental short distance forces. Thaler and collaborators are using a semi-supervised machine-learning strategy called topic modelling to disentangle quark and gluon jets produced in heavy-ion collisions.

The string and quantum gravity group in the CTP has made progress in several directions. Netta Engelhardt's work focuses on understanding the emergence and origin of gravitational thermodynamics in dynamically evolving spacetimes such as time-dependent black holes and cosmology, including "calculating the information content of a black hole and its radiation," for which she won a 2021 New Horizons in Physics Prize. Daniel Harlow uses tools from string theory, quantum field theory and quantum information theory to understand quantum properties of black holes and the structure of spacetime on the largest scales. Harlow and collaborators recently clarified the relationship between holography and Euclidean quantum gravity. Washington Taylor and collaborators have completed a paper giving a general Weierstrass model formulation of F-theory models with a tuned gauge group, which gives a broad class of string constructions with standard model gauge group and matter content that includes the fields of the Minimal Supersymmetric Standard Model. Barton Zwiebach has solved the problem of the conformal field theory calculation of the off-shell three-string vertex, needed for computations in hyperbolic geometry.

Alan Guth developed a method to speed up the generation of sample field configurations for hybrid inflation models by more than a factor of 100. Power spectra can now be calculated to a part in 10^{16} accuracy. Hong Liu continues to work at the interface of string theory/quantum gravity, nuclear physics, and condensed matter physics; he has developed effective field theories for systems with a 1-form symmetry and used them to discover new effects of magnetic diffusion. Frank Wilczek has wideranging interests, including the study of anyons (a quantum quasiparticle he proposed decades ago), experimental evidence for which was reported in the last two years by two different groups.

Quantum information and quantum computation is a growing effort in the CTP with connections to many other areas of the Department of Physics, as well as other departments at MIT. 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. Aram Harrow in the CTP carries out forefront work in these areas.

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

The US Department of Energy 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, physicists, and technicians have completed design work on the MVTX detector for the sPHENIX experiment at BNL and are now overseeing manufacturing of components. The detector itself is a cylinder formed of 48 staves, supported off a long carbon fiber cylinder that reaches inside the sPHENIX magnet, surrounding the beam pipe that carries colliding ion beams. A mock-up of the MVTX is being built to test methods and supports for inserting the MVTX into the sPHENIX setup and to ensure there are adequate clearances as the MVTX must fit in a small region between the beam pipe and the neighboring detector. Members of the MIT HIG are collaborators on the sPHENIX experiment.

The mockup of the MVTX detector support structure to test the MVTX insertion mechanism and verify clearances to other sPHENIX detectors and the RHIC beamline. The support structure splits in half along its length as the beamline will already be in place when the MVTX is installed. The MVTX detector itself would be at the far end of the support structure at the top of the photo. The ring at the near end of the support structure will mount to support arms outside the sPHENIX magnet and detector package. The two semicircular plates with holes (to the right of the mockup) are to be mounted to the near end of the support structure to provide support for cables and cooling lines that run down the support structure to the MVTX detector.

Photo: Andrew Gallant

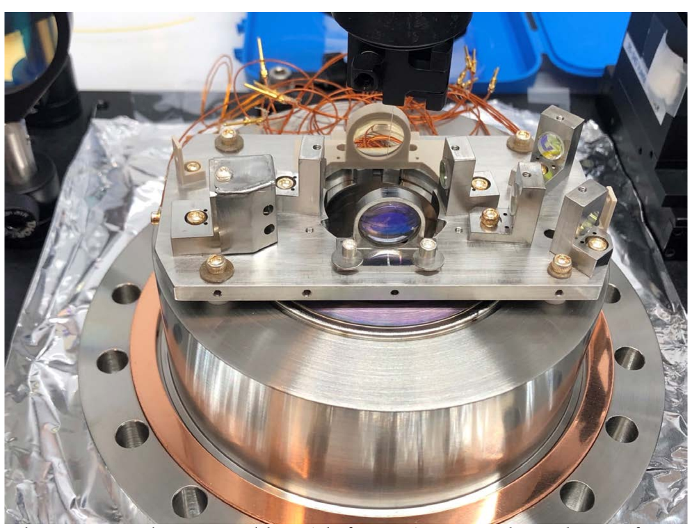
Work began on designing an upgrade to the BEam COoler and LAser spectroscopy (BECOLA) beamline at the Facility for Rare Isotope Beams to enable implementation of the Collinear Resonance Ion Spectroscopy (CRIS) technique there. In addition, MIT-Bates engineers and technicians are supporting design and construction of the beamline for Photo-resonance Excitation and Cavity Ionization Spectroscopy Apparatus, a research and development effort by Ronald Garcia Ruiz to further develop the CRIS technique.

After some improvements, MIT-Bates engineers have completed testing on the Atomic Beam Source (ABS) for the neutron electric dipole moment (nEDM) experiment in collaboration with members of the MIT Hadronic Physics Group. The experiment is planned to run at the Oak Ridge National Laboratory, and the ABS will provide polarized ^{3}He to be used as a co-magnetometer in the experiment. The engineers are now working on design modifications to allow the ABS to operate in a vertical orientation, as required by the current nEDM plans. Furthermore, MIT-Bates physicists, engineers, and technicians have made contributions to many of the experiments discussed above.

The high-performance research computing facility at Bates supports 71 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power for LHC data analysis, lattice QCD calculations, the MIT Geospatial Data Center in the Department of Civil and Environmental Engineering, the Department of Chemical Engineering, and for other LNS research uses.

MIT Central Machine Shop

The Laboratory for Nuclear Science operates the MIT Central Machine Shop (CMS) as a service center. The CMS is widely used across the Institute to build research-related equipment, as well as performing work for the Department of Facilities and research facilities from off-campus sites. One example is the bow-tie cavity to study laser-atom interactions for a group in the Department of Physics and the Research Laboratory of Electronics. The apparatus contains four mirrors that amplify laser light to increase the laser intensity at the location of the atoms whose properties are being studied; two lenses collect light emitted by the atoms.



The support plate assembly with four mirrors and two lenses for the bow-tie cavity. The assembly is mounted on a vacuum flange. Photo: Andrew Gallant

Another project involved making components for the MVTX detector for the sPHENIX experiment, designed by engineers at MIT-Bates, including the end-wheels that support the detector staves.

Half of the end-wheel supports for one layer of silicon detector staves in the MVTX detector; the beamline runs through the axis of the semicircle.

Identical supports are used on the other side of the beamline.

These two supports mount on either end of the staves.

The ten staves are held at an angle (relative to the perpendicular to the beamline) by the machined ledges.

Photo: Andrew Gallant

This project required holding tight tolerances to ensure good knowledge of the detector stave positions.

Education

Since its founding, LNS has placed education at the forefront of its goals. In the past year, approximately 87 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 of nuclear and particle physics in this country and abroad.

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