Laboratory for Nuclear Science

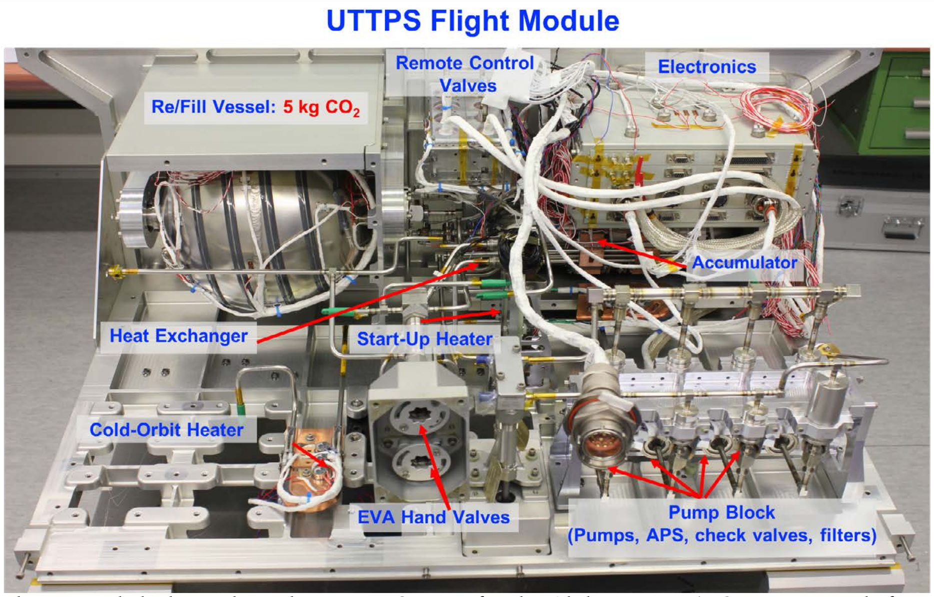
The Laboratory for Nuclear Science (LNS) provides support for research by faculty and research staff members in the fields of particle, nuclear, and theoretical plasma physics, as well as quantum information theory. This includes activities at the MIT-Bates Research and Engineering Center and the Center for Theoretical Physics (CTP). Almost half of the Department of Physics faculty conduct research through LNS. Fiscal year 2020 saw the campus-wide shutdown in March of all but essential services due to the COVID-19 pandemic. For LNS, essential research services focused on keeping computer services running and remotely accessible. Prior planning and hard work by several computing professionals and technicians maintained access to financial systems, research computer 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 resumed in June at less than 25% capacity, consistent with phase 1 of MIT's Research Ramp-Up program.

During FY2020, total research volume using funding provided by the US Department of Energy (DOE), the National Science Foundation (NSF), and other sources was $19.9 million, a decrease of about $1.5 million from the previous year. A portion of this decrease is due to the completion and launch in November 2019 of the replacement thermal pump system for the Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS), and a portion to reduction in travel and delays in hiring due to the COVID-19 pandemic. LNS researchers are successfully pursuing multiple funding opportunities that should maintain or even increase research volume in the future. Some LNS faculty have successfully pursued foundation funding to compensate for reductions in the availability of federal funds; foundation funding typically runs through the Department of Physics and therefore does not appear as LNS research volume. Five LNS junior faculty currently hold prestigious Early Career/CAREER Awards from DOE and NSF; two of them—Professors Tracy Slatyer and Yen-Jie Lee—have been designated as recipients of the Presidential Early Career Awards for Scientists and Engineers. Professors Yen-Jie Lee and Lindley Winslow received tenure in the past year.

Experimental Particle Physics

LNS researchers in experimental high-energy particle physics are active at CERN in Geneva, Switzerland, at the Fermi National Accelerator Laboratory 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 (SM). 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 experiment (AMS-02), 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 ISS. AMS has been collecting data since 2011, and has collected over 150 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. A major focus of the group for the past several years has been design, construction, and testing of a replacement thermal cooling system for the silicon tracker detector, called the Upgraded Thermal Tracker Pump System (UTTPS).



The Upgraded Thermal Tracker Pump System for the Alpha Magnetic Spectrometer, before the cover was mounted. The various components are labeled. Photo by Zhan Zhang.

The UTTPS was launched to the ISS in November 2019 from Wallops Island, Virginia. Astronauts took four Extra Vehicular Activity (EVAs) or spacewalk, over several months to remove the existing cooling system and install the UTTPS.

European Space Agency astronaut Luca Parmitano with the Upgraded Thermal Tracker Pump System (UTTPS), while on an Extra Vehicular Activity to mount the UTTPS on the Alpha Magnetic Spectrometer on the International Space Station.

Photo from NASA.

Results have been published this year on properties of cosmic ray helium isotopes, and properties of neon, magnesium, and silicon primary cosmic rays. Data will continue to be collected on electrons, positrons, protons, antiprotons, helium, and other nuclei and antinuclei until the end of ISS operations, 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, the 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 2021.

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.

Other LNS researchers are working on the 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. 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 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

In addition to long-standing programs in heavy-ion physics, hadronic physics, and fundamental properties, LNS now has a program in low-energy nuclear structure with the addition of Professor Ronald Garcia Ruiz this year. He 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.

LNS researchers are prominent in relativistic heavy-ion physics. The Heavy Ion Group (HIG) plays leading roles in the CMS experiment heavy-ion program at CERN and the Super Phenix (sPHENIX) collaboration at Brookhaven National Laboratory (BNL) in New York. Physics results in FY2020 include the first measurements sensitive to beauty-strange quark recombination; the first measurement of charged particle multiplicity distributions in XeXe collisions, testing the size and geometry scaling of hadron production; the first exotic meson measurement in relativistic heavy ion collisions; and the first measurement sensitive to nuclear modification of the charm jet structure. At BNL, sPHENIX will be used to study jet quenching in heavy ion collisions, in a complementary fashion to CMS. sPHENIX equipment is in the final design stages and construction has begun. 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, Jefferson Lab, the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee, the Mainz Laboratory in Germany, and the Large Hadron Collider beauty experiment at CERN. The main thrust of these experiments is a detailed understanding of the properties of the proton, the neutron, and light nuclei.

For two decades, MIT nuclear physicists have been active in a plan to develop the next-generation accelerator facility to study the fundamental structure of matter. In January 2020, DOE gave approval for the Electron Ion Collider (EIC) project to proceed. The EIC can be thought of as an electron microscope that will explore important questions about protons and neutrons (nucleons) as many-body complex systems: how does the mass of the nucleon arise?; how does the spin of the nucleon arise?; and what are the properties of dense systems of gluons, the carriers of the strong force between quarks, which bind together to form nucleons? The EIC will be built at Brookhaven National Laboratory, with operation for experiments expected in the early 2030s. Many members of LNS from medium energy nuclear physics, heavy ion physics, theoretical nuclear physics and technical staff from MIT-Bates expect to be involved in design and construction of the accelerator and experimental equipment, and 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 Cryogenic Underground Observatory for Rare Events (CUORE) collaboration at Gran Sasso, Italy, and the KamLAND-Zen collaboration at the Kamioka Observatory in Japan, searching for neutrino-less double beta decay (NDBD). If observed, this would imply the neutrino is its own antiparticle. Analysis of CUORE data to date sets a limit of 3.2×10^{25} years for the NDBD lifetime, corresponding to an effective Majorana mass of 75-350 meV. MIT physicists are also playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment at 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 1 eV/c^2 at 90% confidence level; 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 seeks to extend and unify our understanding of fundamental physics, through activities spanning many research areas. Netta Engelhardt, a general relativist who has developed a new framework for understanding black hole horizons and related puzzles, joined CTP as an assistant professor in July 2019.

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 SM only describes 5% of the mass-energy in the observed universe, does not explain how gravity fits into the framework of quantum physics that underlies the SM, 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 SM 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. And there are many puzzles related to quantum physics, black holes, and other accepted features of the SM 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 that focus on calculating key properties and interactions of nucleons and light nuclei. This past year, Shanahan and Detmold have continued efforts on calculations relevant for neutrino-less double beta decay, and investigated interactions between charged and neutral mesons and baryons. Shanahan and Detmold have also continued to investigate new ways of performing lattice QCD calculations faster using sparse data objects, machine learning, and custom hardware. Professor 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. This past year he and his collaborators have developed the Hydro+ formalism to characterize the formation of the quark-gluon plasma, where there is a transition from a highly non-equilibrium state with a few prehydrodynamic modes into a fluid described by hydrodynamics. Professor 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. This past year his activities included introducing a new class of jet substructure observables, collinear drop, which provide a sensitive probe for soft radiation effects within jets, including those from hadronization, pileup, and from whether the jet is initiated by a quark, gluon, or color neutral decaying particle, or is transversing a medium as in heavy-ion collisions.

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 and 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 SM. During the past year, Slatyer has continued her program of building a comprehensive set of tools for predicting the signatures of dark matter physics in the Milky Way and in the early history of our universe. This includes a new public code package, DarkHistory, which self-consistently solves for the secondary particle cascade induced by injection of high-energy particles and follows the evolution of cosmic ionization and temperature. Another active area of research of the MIT group, and in particular Professor 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. Over the past year he and his group introduced Energy Flow Networks, a machine learning architecture to approximate jet observables, and OmniFold, which uses machine learning to correct for detector effects in collider data.

The string and quantum gravity group in the CTP has made progress in several directions. Assistant Professor 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. Assistant Professor 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. Engelhardt and Harlow collaborate in areas such as improving our understanding of entanglement shadows in bulk spacetime. Professor Washington Taylor and his group continue to work on a program of identifying fundamental constraints from string theory on how matter fields can be charged under gauge forces, and in particular finding ways in which string theory imposes constraints that are not apparent in quantum field theory. Professor Barton Zwiebach has continued to develop his new program of computing previously unknown minimal area metrics on certain surfaces that describe Feynman diagrams of string field theory, and in cosmology has recently classified all higher-derivative corrections in a theory reduced so that all fields just depend on cosmic time.

Other work in the CTP focuses on quantum systems, quantum information, and quantum computing. Recently, Professor Alan Guth has continued to study the generation of primordial black holes in the context of hybrid inflation, via numerical simulation. Professor Hong Liu continues to work at the interface of string theory and quantum gravity, nuclear physics, and condensed matter physics. Professor Frank

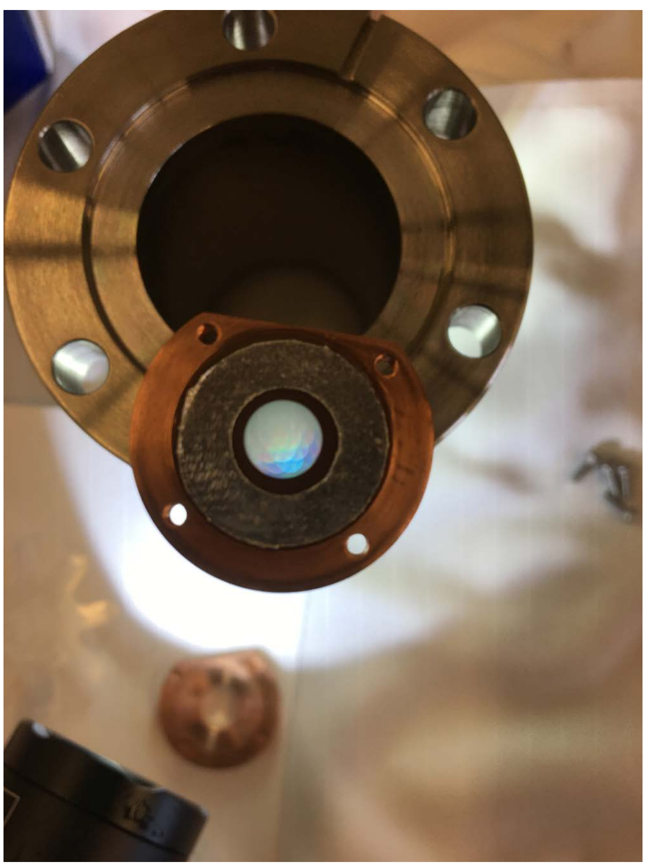
Wilczek has wide-ranging interests, including the study of anyons, a possible third type of quantum particle in addition to bosons and fermions.

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 such applications as quantum cryptography, and with basic theoretical questions about quantum information and quantum entanglement. Professor Aram Harrow in the CTP carries out forefront work in these areas. One recent investigation with a student looked at how much a quantum computer can speed up a Markov Chain Monte Carlo algorithm. Professor Harrow's work on quantum information also connects with that of Professor Harlow, who earlier demonstrated that ideas associated with quantum error correction play a role in the holographic framework for quantum gravity, and with that of Professor Thaler, through the application of quantum technology to algorithmic problems in jet clustering.

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 Research and Engineering Center



The microchannel plate nozzle being prepared for testing in the Atomic Beam Source for the nEDM experiment. The microchannel plate itself is held by an indium washer in the copper holder; the back-lighting generates a faint rainbow pattern in the center of the indium holder, due to the many tiny holes in the microchannel plate. The copper holder will be mounted inside the stainless steel vacuum chamber on which it rests in the photo.

Photo from James Kelsey.

DOE provides base support for a research and engineering center where US nuclear physicists, including LNS faculty and their collaborators, and development of 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 are testing and making improvements to the Atomic Beam Source (ABS) for the neutron electric dipole moment (nEDM) experiment, planned to run at the Oak Ridge National Laboratory. The ABS will provide polarized helium-3 to be used as a co-magnetometer in the experiment. One improvement being made to the ABS is changing out the original nozzle (a bundle of fine, straw-like needles) that directs helium-3 into a long quadrupole that selects a certain polarization state for a microchannel plate nozzle.

The microchannel plate was designed by MIT-Bates engineers. The plate itself is an 18 mm diameter glass disk with approximately four million pores, each 10 microns across; the exposed portion of the disk is about 13 mm in diameter. The expectation is that this will substantially increase the flux density of helium-3 in the quadrupole chamber. Members of the MIT Hadronic Physics Group are collaborators on the nEDM experiment.

MIT-Bates engineers are finalizing design of the support structure and services for the Monolithic Active Pixel Sensors detector for the sPHENIX experiment at BNL. As mentioned above, sPHENIX is one of the experiments being pursued by the MIT HIG. 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 70 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power for LHC data analysis, lattice QCD calculations, ocean and climate modeling by a group in the Department of Earth, Atmospheric and Planetary Sciences, computational fluid dynamics relative to ship hull design for the MIT Sea Grant program, the MIT Geospatial Data Center, and for other LNS research uses.

MIT Central Machine Shop

An autonomous bicycle prototype; the linear actuator that shifts the wheels from autonomous mode (angled for balance, as shown) to being vertical for a rider is located below where the seat post meets the crossbar.

Photo by Andrew Gallant.

LNS 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 Facilities Department and research facilities from off-campus sites. The work ranges from small to large jobs, complex jobs, or a combination of such, that require precision machining, such as working with the City Science group at the MIT Media Lab to build an autonomous bicycle. This can be ridden as an ordinary bicycle and then when the user reaches their destination, the rear wheel separates to a tricycle configuration and the bike takes itself to the next user or a distribution and charging station.

Another project involved making a dummy, low-enriched uranium (LEU) fuel element for the MIT Nuclear Reactor Laboratory and the Department of Nuclear Science and Engineering. This dummy element will be used to assess differences between the existing highly-enriched uranium fuel elements, and the new LEU design.

End view of a dummy LEU fuel element. The thin plates inside the structure would, in a real fuel element, contain uranium in long thin rods, with gaps for coolant to flow between the rods and between the plates.

Photo from Andrew Gallant.

Education

Since its founding, LNS has placed education at the forefront of its goals. In the past year, approximately 82 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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