Overview of Fundamental Physics at LANSCE

Martin D. Cooper and W. Scott Wilburn

Experiments to elucidate fundamental physics have had a long history and are expected to have an exciting future at the Los Alamos Neutron Science Center. This overview discusses a selection of past, current, and future experiments exploring the validity of the standard model of strong and electroweak interactions and possible physics beyond that model. It concludes with a look at how current experiments are stimulating plans for the future. The current experiments are then further described in the short articles that follow.

Experiments to elucidate the fundamental physics of elementary particles at the Los Alamos Neutron Science Center (LANSCE) began about 30 years ago, when the facility was called the Los Alamos Meson Physics Facility (LAMPF) and its operation had just recently begun. At that time, the Standard Model describing the known phenomenology of elementary particle physics (Figure 1) was still in the making. Groundbreaking high-precision experiments were performed at LANSCE to explore the symmetries and dynamics of the Standard Model, especially the electroweak part, which unifies the description of the weak and electromagnetic forces. LAMPF produced a very intense source of muons and neutrinos (from the decay of pi mesons, also called pions), ideal for testing the new electroweak theory and for exploring the limits of the observed family symmetry.

Today, the spotlight at LANSCE has shifted to neutrons and to studies aimed at discovering physics not explained by the Standard Model—such as the prevalence of matter over antimatter in our universe. Although relatively old by most standards, LANSCE remains a premier facility for conducting state-of-the-art experiments. Its proton beam power has remained one of the highest in the world. The intense flux of neutrons released when those protons strike a heavy-metal target continue to make possible very high precision measurements, as well as searches for rare processes predicted by theories that go beyond the standard model. Los Alamos National Laboratory has also built up a unique cadre of first-rate scientists with the desire and know-how to design and perform these difficult experiments, including the suppression of myriad systematic effects that could wipe out the signals of interest.

Fundamental physics is the study of the four known forces in nature. In order of strength, they are the strong (nuclear) force that binds neutrons and protons (nucleons) into a nucleus and is responsible for nuclear reactions such as fission and fusion; the electromagnetic force that governs all of chemistry and everything from light waves to magnets; the weak force that induces radioactive decay; and the gravitational force that binds the universe together. When physicists try to write a mathematical description of the forces, they need to know their strengths, their behavior as a function of distance between affected objects, and the transformation properties under symmetry operations.

The Standard Model is a quantum mechanical description of the strong, weak, and electromagnetic forces. It divides the known elementary particles in nature into those that carry the force and those that are affected by the force (Figure 1). For example, the electromagnetic force between two charged particles is described as an exchange of photons between them; in other words, the photons carry the force. Similarly, the weak force is carried by the *W* and *Z* bosons, and the strong force is carried by the gluons. The particles affected by the forces are the quarks and the leptons. The quarks make up the hadrons—neutrons, protons, and other heavy particles—that interact primarily through the strong force and less strongly through the other three forces. In contrast, the leptons (light particles including the electron, its neutrino partner, and their heavier cousins) are unaffected by the strong force in the same way that neutral particles such as the neutron and the neutrino are immune from electric attraction or repulsion. The fact that the elementary particles interact differently greatly assists in separating the properties of the forces. Figure 1 shows a diagram of how the quarks and leptons are grouped in three families, or generations, with each family composed of two quarks and two

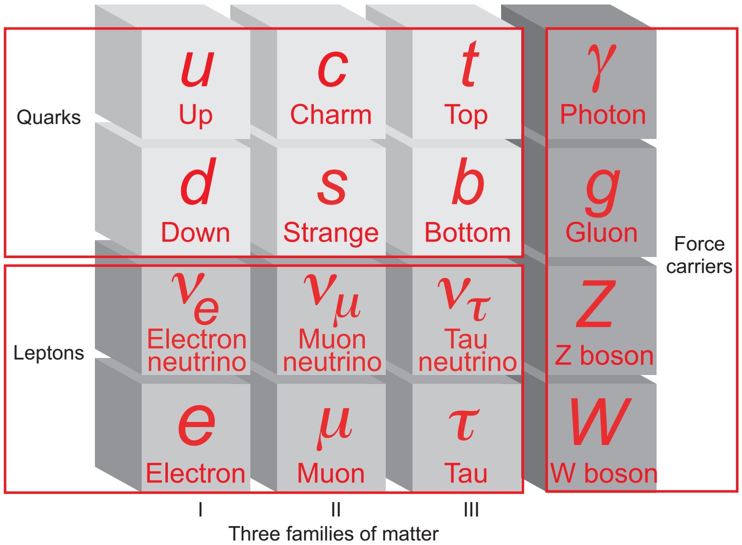

Figure 1. The Standard Model Illustrated
The fundamental particles are divided into those that are affected by the strong and electroweak forces, the quarks and leptons, and those that mediate, or carry, the forces. The quarks and leptons are arranged to illustrate their periodic character, or family structure. Families II and III have been shown to be reproductions of family I but with increasing mass. Within each family, the quarks and leptons are arranged from the heaviest on top to the lightest on the bottom to indicate the way the heavier particles decay through the electroweak force. A number of discoveries remain to be made that will reveal whether this picture is complete or whether extensions to the Standard Model are required.

leptons. The lightest family comprises the up and down quarks (that make up the neutron and the proton) and the electron and its partner, the electron neutrino. The other two families have identical properties (quantum numbers) except for being heavier particles and carrying a family identity. One of the great mysteries of the Standard Model is why there is a threefold reproduction of the basic family structure.

Examples of Past Experiments

The historical record at LANSCE contains many significant experiments. The four examples described below demonstrate the strengths of the facility today.

Testing the Family Symmetry. The family symmetry arises from the observation that the number of members of a given family remains constant (where particles of a family have family number +1 and antiparticles have family number –1). Thus, particles of one generation do not transform into particles of another generation unless another family member is created. For example, a muon from family II cannot decay into an electron without the emission of a muon neutrino to conserve the number of family II members or without the emission of an electron antineutrino to conserve the number of family I members. Thus, the decay $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ occurs in nature. This apparent conservation law has no known physical basis, and the recent discovery of neutrino oscillations in which electron neutrinos can transform into muon and tau neutrinos and vice versa proves it is not exact. However, though the family symmetry is broken, the violation is extremely small. The archetype process that appears to be forbidden is the decay of a muon into an electron and a gamma ray.

In 1978, it was known that $\mu \rightarrow e + \gamma$ does not occur at the level of two decays in 10^8. Physicists have good reason to believe that the Standard Model is incomplete, and many models of its extension predict that $\mu \rightarrow e + \gamma$ should happen at measurable levels. A series of experiments were mounted at LANSCE between 1978 and 1995 to search for $\mu \rightarrow e + \gamma$ with ever-increasing sensitivity. All these experiments took advantage of the intense beams of muons extracted from the Stopped Muon Channel. They shared some common features based on the unique signature of $\mu \rightarrow e + \gamma$, the detection of a gamma ray and an electron with precisely half the energy of the muon mass, the electron and the gamma ray traveling back to back in opposite directions and being coincident in time. All the experiments used electron and gamma-ray detectors that provided good resolution of energy, time, and position of the decay products. Each successor experiment improved the resolutions to more sensitively isolate the $\mu \rightarrow e + \gamma$ process from a variety of backgrounds. The final experiment, known as MEGA, improved the sensitivity to one decay in 10^{11}, three orders of magnitude better than the 1978 value. These investigations by Los Alamos staff and many university collaborators severely constrain the types of extensions to the Standard Model that observation tolerates.

Measuring the Strength of the Weak Hadronic Force. Physicists have determined that the symmetry properties of the forces are the keys to understanding the forces. For example, the weak force violates mirror symmetry, or parity, the symmetry that postulates that a process and its mirror image should be equally likely. In fact, this "parity violation" by the weak force is observed to be as large as possible. Because parity violation is unique to the weak force, measuring the degree of parity violation in a given process can be used to identify the influence of the weak force in the presence of the dominant strong force. The TRIPLE collaboration (a team from Los Alamos and many other institutions) used that approach to determine the strength of the weak force between hadrons (neutrons and protons) in heavy nuclei. That measurement is of great interest as a check against the best calculations to see if the complicated effects of the strong force can be accounted for properly.

The team measured the cross section for polarized epithermal neutrons (spins pointing in one direction and energies of approximately 1 electron volt) to undergo resonant absorption in heavy nuclei. Such neutrons are absorbed by populating many unstable states in compound nuclei. Varying the direction of neutron polarization resulted in the effects of the weak force becoming apparent. The depletion of the neutron beam by the target depended on the direction of the neutron spins relative to their direction of motion, a violation of mirror symmetry. Because so many nuclear states exhibited parity violation, the extracted strengths for the weak interaction could be treated statistically. Such an analysis allowed for the extraction of the parameters that characterize the average weak interaction in heavy nuclei. Good agreement was achieved with measurements in other systems. J. David Bowman of Los Alamos National Laboratory received the Bonner Prize in nuclear physics for this work.

Measuring Alpha, the Strength of the Electromagnetic Force. The strength of the electromagnetic force is measured by the fine structure constant, alpha. One of the most accurate ways of measuring that constant is in an atom made of leptons because the strong interaction plays no role in such a system. An atom with this property is muonium, in which a positive muon binds an electron to make a neutral atom. Muonium has been extensively studied by a LANSCE collaboration led by Yale University and the University of Heidelberg. To extract alpha, the team measured the hyperfine splitting of muonium energy levels when placed in a magnetic field.

Muonium was produced by taking the lowest-energy positive muons from the Stopped Muon Channel and stopping them in krypton gas. A small fraction of the muons would capture electrons and form muonium. The stopping region was contained in a microwave cavity whose frequency was adjusted to populate the hyperfine states with a preselected direction of muon spin. The weak decay of the polarized muons produced an asymmetric angular distribution of electrons due to parity violation, which reflected the relative population of the hyperfine states. The energy separation of the states was determined by adjusting the frequency of the microwave cavity for a resonance condition. The precise measurement of the energy splitting allowed the extraction of alpha with a precision of 58 parts per billion, competitive but not quite as good as the value of alpha obtained by other methods. Such precise measurements have led to the most stringent tests of quantum electrodynamics.

Detecting Neutrino Oscillations. There have been a series of experiments to study neutrino properties at LANSCE. The most recently completed was the Large Scintillating Neutrino Detector (LSND). The LSND project invented a novel technique of mixed Cerenkov and scintillation light detection to separate the neutrino signal from backgrounds. LSND reported neutrino oscillations arising from a (squared) difference in mass between two neutrino species of approximately (1 electron volt)^2. This result has been highly controversial because the current three-neutrino model allows for only two independent mass differences, which have been established in solar and atmospheric oscillation experiments and disagree with the LSND value. If proven correct by experiments elsewhere, LSND would have discovered the existence of a fourth neutrino with revolutionary properties. Such a particle would induce a dramatic change to the Standard Model, possibly destroying the categorization represented in Figure 1.

Current Experiments

LANSCE has evolved into a world-class neutron facility since 1995, and three high-profile neutron experiments are currently underway that build on past experience in fundamental physics.

An Ultracold-Neutron (UCN) Source and Measurements of Neutron Properties. UCNs are neutrons with such low energies that they can be held in a bottle—energies below 200 billionths of an electron volt or 200 nano–electron volts (neV). The bottle walls can be made from material, magnetic fields, or the gravitational force. All three confinement methods of UCNs are being exploited at LANSCE. Such low-energy neutrons are very hard to produce in great numbers. A new technique, known as the super-thermal method, is being pioneered at LANSCE. The method scatters cold neutrons from very cold (5 kelvins) solid deuterium. The cold neutrons lose energy and become UCNs exciting phonons (vibrational waves) in the solid deuterium. A prototype of the facility produced a world record in UCN density.

The UCN facility is currently being commissioned to measure the decay properties of polarized neutrons. These ultralow-energy neutrons allow us to search with increased sensitivity for significant deviations from Standard

Model predictions that could indicate the existence of new particles and modify our understanding of the weak force. This experiment is due to take data next year. The facility will also be used to make a more precise measurement of the neutron lifetime. The neutron lifetime is an essential component of determining the weak interaction between quarks. Its value also has implications for the cosmological origin of the light elements.

Neutron Electric Dipole Moment. Determining the value of the neutron electric dipole moment (EDM) has long been considered a seminal experiment. The existence of this quantity at values greater than predicted by the Standard Model requires further violations of time reversal symmetry, which would have important consequences for modern theories of particle physics such as supersymmetry and for the origin of the matter–antimatter asymmetry of the universe. Los Alamos is leading the development of a new technique to improve experimental sensitivity to the EDM by two orders of magnitude. An extensive research and development program has been underway to demonstrate the feasibility of this goal. Several parts of the demonstration have taken place at various neutron sources at LANSCE.

Strength of the Weak Hadronic Force between Two Nucleons. The strength of the hadronic weak interaction remains a puzzle because of conflicts among the methods for determining it. A direct and definitive method for measuring the strength of the weak hadronic force in the neutron-proton system is underway at LANSCE's Lujan Center. The method takes cold neutrons from the cold source, polarizes them, and has them captured in a hydrogen target. By looking at the asymmetry in gamma-ray production associated with deuteron formation, the quantity of interest is extracted with little theoretical uncertainty.

These three efforts have the current staff in fundamental physics fully engaged for the near term. As described below, the next generation of scientists has an exciting future awaiting them at LANSCE.

Future Directions

LANSCE has a long tradition of evolving its capabilities to take advantage of changes in facility operations. Four areas of fundamental nuclear physics—nuclear astrophysics, cold neutron physics, ultracold neutron physics, and neutrino physics—are currently being evaluated. They are well matched to upgrades under consideration for LANSCE. Facility improvements being sought for materials science research and advanced proton radiography for nuclear weapons research would naturally lead to enhanced capabilities in nuclear astrophysics and fundamental physics with cold neutrons.

As the current UCN source achieves its full potential, producing UCN densities of approximately 100 per cubic centimeter (cc), it will be used to perform the UCNA experiment, which will measure the electron asymmetry in polarized-neutron beta decay. Further upgrades will then be explored. Increases in the flux of protons delivered to the facility, improvements in UCN production efficiency, and use of novel production targets may ultimately provide UCN densities of approximately 1000 per cc for multiple simultaneous experiments. Such an apparatus would be a true UCN user facility and would open new opportunities for testing the Standard Model of electroweak physics using neutrons.

We know that neutrinos have mass from the observations that they are created and destroyed as states of definite "flavor" (electron, muon, or tau type) but propagate as states with definite mass. Because the flavor and mass states are not perfectly aligned, neutrinos can change flavor as they propagate through vacuum or matter, a process that would not be possible if neutrinos were massless. These flavor oscillations were possibly glimpsed in the LSND experiment at LANSCE and have since been definitively seen in solar and atmospheric neutrino experiments. Mapping out the full set of fundamental neutrino parameters will require new experiments with more intense fluxes of neutrinos than have previously been available. These parameters are the mass differences between neutrino types, angles that describe the degree of mixing between flavors, and a possible charge-parity symmetry (equivalent to time reversal symmetry) violating phase that may be related to the differing amounts of matter and antimatter in the early universe.

Very intense, pulsed beams of neutrinos can be produced with existing technology by directing proton beams with megawatt power onto material targets to produce an intense source of pions and then focusing those pions with electromagnetic horns. Construction of the requisite "proton driver" in the United States has been recommended in a recent American Physical Society report. Several national laboratories in the United States, Europe, and Japan are pursuing such a facility; however, a decision to build a U.S. facility has not yet been made. If LANSCE were to upgrade the power of its existing proton beam, an improvement that is also sought for other areas of research, a proton driver would be a natural extension. A study will be conducted in the near future to evaluate the scientific case for building this facility at LANSCE. ■