Excerpts from Mission Need Statement for a Muon to Electron Conversion Experiment

Office of High Energy Physics
Office of Science

As the Large Hadron Collider (LHC) commences operations we anticipate the possibility of profound new discoveries that will change the way we view the submicroscopic world. Additional experimentation will be needed to understand the detailed nature of the LHC discoveries or to probe higher mass scales should new discoveries prove elusive. The conversion of a muon to an electron in the field of a nucleus provides a unique window on the structure of potential new physics discoveries and allows access to new physics at very high mass scales. The Particle Physics Project Prioritization Panel (P5) identified this opportunity as a top priority, but no capacity currently exists to exploit such a measurement.

The mission of the High Energy Physics program is to understand how our universe works at its most fundamental level. We do this by discovering the most elementary constituents of matter and energy, exploring the basic nature of space and time itself, and probing the interactions between them. The Energy Frontier directly explores the fundamental constituents and architecture of the universe using very high energy particle accelerators. The Intensity Frontier, accessed with a combination of intense particle beams and highly sensitive detectors, offers a second unique investigation of fundamental interactions through the observation of very rare processes. Such investigations help to interpret physics discovered at the energy frontier and indirectly reveal phenomena that cannot be observed at the energy frontier. A muon to electron conversion experiment can probe new physics at mass scales that exceed the reach of the LHC by a factor of 1000.

The physics program enabled by a muon to electron conversion experiment is fully consistent with the Secretarial Strategic Priority of Science, Discovery, and Innovation. The program would demonstrably “Advance fundamental knowledge in high energy physics and nuclear physics that will result in a deeper understanding of matter, energy, space and time.”

One of the great puzzles in high energy physics is the existence of three generations of particles with similar properties but very different mass scales. Each generation has a pair of quarks, a lepton, and a neutrino. Transformation of the particles from one generation to another, often called “flavor violation”, has been observed in the quark and neutrino sectors. Quark flavor violation has been studied for more than thirty years and was the basis of the 2008 Nobel Prize. Recently flavor violation was also discovered in neutrino experiments, where the three generations of neutrinos are observed to oscillate into one another. Neutrino experiments such as Kamiokande, SNO and KamLAND have observed oscillations among some of the flavors; NOvA hopes to observe the rarest oscillation and open a new line of study.

Neutrinos are neutral leptons. We do not know if flavor violation occurs among charged leptons or how it might relate to new phenomena at the energy scales probed by the highest energy accelerators. The electron is the lightest charged lepton and is one of the building blocks of matter and the source of electricity. We need to understand more about how it behaves to understand these basic constituents of our world.

Theoretical models that incorporate ideas such as unification, super symmetry or heavy-neutrino mixing predict charged lepton flavor violation at rates that are within the reach of new experiments. Combined with results from the Office of Science's high priority neutrino program and the Office's experiments at the LHC, a muon to electron conversion experiment could help point the way to unification of the fundamental forces and shed light on the mechanism for generating the observed matter-antimatter asymmetry of the universe.

The LHC will begin operations in 2009 and will produce physics results over the next decade or more. Feedback from a muon to electron conversion experiment will provide input for future investigations at the LHC, so there is motivation to complete this acquisition in the next decade. This priority was echoed by the P5 subpanel charged by HEPAP to present a strategic plan for High Energy Physics for the next ten years. In their report "*US Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years*" they make the case that this mission need should have a high priority:

> A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude. The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. Development of a muon-to-electron conversion experiment should be strongly encouraged in all budget scenarios considered by the panel.

The need for a detector to search for muon to electron conversion was made clear by the P5 sub panel, referenced above. The P5 sub panel noted that:

> Scientific opportunities through the measurement of rare processes include experiments to search for muon-to-electron conversion and rare-kaon and B-meson decay. Such incisive experiments, complementary to experiments at the LHC, would probe the Terascale and possibly much higher energies.

To address this opportunity P5 recommended:

> Development of a muon-to-electron conversion experiment should be strongly encouraged in all budget scenarios considered by the panel." The Department currently has no capability to perform such an experiment. In order to close this gap, a new detector to measure muon to electron conversion is required.

An intense pulsed proton beam is required to produce a sufficient flux of muons to perform a muon to electron conversion experiment to the sensitivity required for these investigations. The DOE operates the only facilities where such proton beams are available. There are no private entities with the potential to fill the gap. DOE has no means of filling the gap other than initiating a program to acquire a detector to measure muon to electron conversion and operate it at a facility with an adequate proton beam.

Benefits from Closing the Gap

The DOE strategic goal to advance scientific understanding includes a program to investigate the asymmetry of matter and antimatter in the universe as well as to understand the nature of neutrinos. To date lepton flavor violation effects have been observed only in the neutral lepton sector through the phenomenon of neutrino oscillations. In contrast, since the discovery of the muon, the search for charged-lepton flavor violation has been intense, but, to this date, these searches have not discovered evidence of charged-lepton flavor violation.

Indeed, searches for lepton flavor violation have had great historical importance in the evolution of the Standard Model and in constraining new physics extensions. For example, non-observation of the decay $\mu \rightarrow e\gamma$ helped establish the muon as a distinct elementary particle rather than an excited electron and later motivated the search for the muon neutrino, a discovery that earned the 1988 Nobel Prize.

The current Standard Model modified to explain the observed neutrino oscillations, predicts very small rates for charged lepton flavor violating (CLFV) processes. Many models for new physics, for example supersymmetry, predict rates that are measurable by the next generation of experiments. Any observation of CLFV is unmistakable evidence for new, unknown types of physics. CLFV processes can be sensitive to new physics at and well above the TeV scale and are bound to play a key role in uncovering the origin of neutrino masses.

The discovery of neutral lepton flavor violation in the neutrino sector has had a significant impact on our understanding of the universe and is the first definitive example of physics beyond the Standard Model. The discovery of charged lepton flavor violation could be equally important. A detector to study muon to electron conversion is the next logical step and will augment the ongoing neutrino and LHC programs. In concert with the Department's world-class neutrino program the United States will assume a leadership position in the study of lepton flavor violation and its connection to physics beyond the Standard Model and the matter antimatter asymmetry.

Planned Approach

The planned approach is to design a detector to search for muon to electron conversion that is similar to the detector that was designed by the MECO Collaboration. MECO was a National Science Foundation project that was approved to run at Brookhaven National Laboratory. The project was cancelled and the detector was never built, but the Collaboration spent several years studying and optimizing the design and evaluating relevant technologies. The current approach is to start with the MECO design and evaluate possible modifications based on recent advances in technology and value engineering studies.

The detector consists of a series of superconducting solenoids to capture, transport and momentum analyze muons. Various technologies are being considered for the superconducting cable and variants on the cooling scheme are under consideration. In addition to the solenoids there is a tracking detector and a calorimeter. The technologies being considered for the tracking detector include straw tubes and drift chambers. Multiple design options exist for each technology. The technologies being considered for the calorimeter includes various scintillating crystals, lead/scintillator sandwich detectors, and a Cerenkov radiator combined with a finely segmented tracking detector.

While the MECO experiment was planned to be run at the Alternating Gradient Synchrotron at BNL, Mu2e is ideally suited to the Fermilab complex and especially the Debuncher Ring; the optimum time between beam pulses for a muon to electron conversion experiment is roughly twice the muon lifetime of 864 nsec in Aluminum and the circumference of the Debuncher is 1694 nsec. The experiment is better performed at Fermilab than at BNL because of this timing and because of the significantly higher duty factor (90% vs. 50%). This results in lower instantaneous rates in the detector, which reduces backgrounds.

In accordance with the recommendation from the P5 sub panel and the discussion above, it is assumed that the detector for measuring muon to electron conversion will be located at Fermilab. A scheme to use the existing accelerator facility, with some modifications, to provide 8 GeV proton beam to the detector exists and will allow operation without any impact on the simultaneously operating 120 GeV neutrino program (NOvA).

The greatest existing technical risk is associated with the interface of the detector with the high intensity 8 GeV proton beam. The proton beam enters one of the superconducting solenoids and strikes a target located at the center of the solenoid. The target must be relatively thin to maximize the muon yield and must be cooled to avoid melting. Some R&D is required to benchmark heat flow calculations. Particle spray from the proton beam striking the target will irradiate part of the solenoid causing it to heat up and potentially quench. A heat shield has been designed to absorb the particle spray and protect the solenoid coils, but further studies are required to verify that the design is adequate.