The Mu2e Experiment at Fermilab: a Search for Charged Lepton Flavor Violation

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A new experiment, Mu2e, is being developed at Fermilab to measure the ratio of the rate of the neutrinoless, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus,

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

Mu2e expects a four orders of magnitude improvement on the experimental uncertainty in this ratio, providing a stringent test of the SM with an energy scale on the order of thousands of TeV.

The conversion process is an example of charged lepton flavor violation (cLFV), where muon and electron numbers change by -1 and 1, respectively. Until the discovery of neutrino oscillations, lepton numbers in each generation were strictly conserved in the Standard Model (SM) for any interaction. In a simple extension of the SM that includes neutrino oscillations, an extremely small rate of muon to electron conversion is predicted, far below any foreseeable experimental sensitivity. Therefore a non-vanishing signal would be a definite sign of new physics. In most of the proposed models of physics beyond the SM, cLFV is allowed. Better experimental limits on cLFV processes produce ever tighter limits on the available parameters in these models.

Although the existence of lepton generations and conservation of lepton numbers plays a central role in the SM, there is no understanding of the underlying symmetry that causes it. Consequently, lepton flavor has been and continues to be under intense experimental investigation. In particular there is a long history of experimental searches for lepton number violation in interactions with *charged* leptons, especially in muon interactions such as $\mu^+ \rightarrow e^+ + \gamma$, $\mu^+ \rightarrow e^+ + e^+ + e^-$, as well as $\mu^- + A \rightarrow e^- + A$, so far with null results. The current best experimental limit on muon-to-electron conversion, $R_{\mu e} < 7 \times 10^{-13}$ (90% CL), is from the SINDRUM II experiment at PSI[1]. With 3.6×10^{20} delivered protons, Mu2e will probe four orders of magnitude beyond the SINDRUM II sensitivity, measuring $R_{\mu e}$ with a single event sensitivity of 2.5×10^{-17}.

In the typical $\mu^- + A \rightarrow e^- + A$ experiment, low energy negative muons are stopped in a thin aluminum target and are captured into the 1S atomic orbital.
The conversion of a muon to an electron in the field of a nucleus occurs coherently, resulting in a monoenergetic electron near the muon rest energy that recoils off of the nucleus in a two-body interaction. In comparison with $\mu^+ \rightarrow e^+ + e^+ + e^-$ and $\mu^+ \rightarrow e^+ + \gamma$, this distinctive

signature has several experimental advantages including the near-absence of background from accidentals and the suppression of background electrons near the conversion energy from muon decays.

There are several new features being implemented that will lead to the planned large increase in sensitivity.

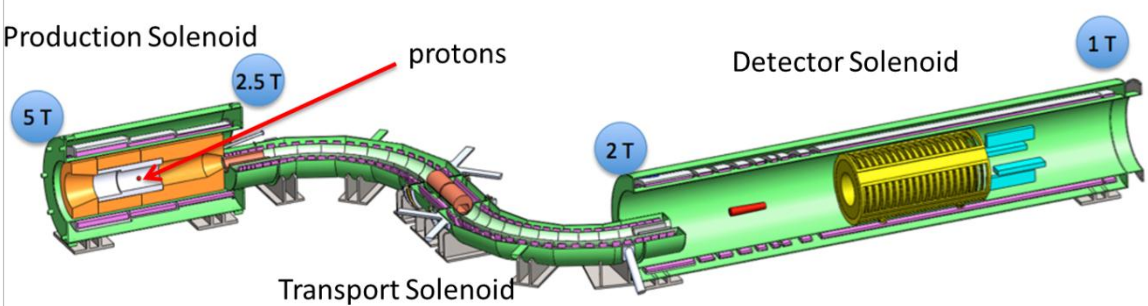
1) The muons will be produced by a pulsed proton beam, which will allow the suppression of a potentially large background from pions.

2) The pulsed proton beam will be intense and will have a good duty factor.

3) The detectors are designed to avoid the large flux of low energy particles emanating from the stopping target, and to provide good particle ID and electron momentum reolution of less than about 1 MeV FWHM.

4) A new muon beam line is being developed, using superconducting solenoids, which collects low energy muons far more efficiently than conventional dipole-quadrupole beam lines.

The proposed Mu2e muon beam and detector layout is shown in the Figure.



Protons enter the Production Solenoid (PS) from the upstream direction. Both pions and muons are captured in helical orbits in the PS, and many spiral downstream through the Transport Solenoid (TS) into the Detector Solenoid (DS), and stop in the aluminum target. Conversion electrons are momentum analyzed by a tracker in the DS magnetic field and then strike a calorimeter. Particles drift up or down in the curved parts of the TS, depending on their charge, and by an amount that depends on the transverse component and total momentum . The desired low momentum negative muons are selected by an off-center collimator in the middle straight section of the TS. The beamline will provide about 0.002 stopped muons per incident proton.

The Mu2e collaboration consists of over 120 scientists from 26 institutions around the world. The experiment has CD1 approval from the US DOE and design work is moving forward. In particular extensive solenoid design and background and signal simulations have already taken place. First beam is expected before the end of the decade. Note that the operation of Mu2e does not interfere with the neutrino program at Fermilab; a proton beam line is being developed that allows Mu2e to utilize beam that otherwise would go unused.

Because of favorable experimental circumstances, there is the potential to improve muon to electron conversion another two orders of magnitude or more, which is likely well beyond the sensitivity to cLFV attainable in other channels. This would require a x100 more intense pulsed proton beam, such as the beam being proposed for Project X, and improved muon collection schemes, such as those that are being developed by the MICE (UK) and MAP (Fermilab) programs. In particular, it would be helpful to develop a high efficiency, low energy negative muon beam that is free of pions. Detector geometries would have to be developed that avoid most of the backgrounds. One such scheme has been proposed in Japan (PRISM/PRIME), based on an FFAG muon storage ring. The nature of these upgrades will of course be guided by the results from the first round of Mu2e and COMET results. In the absence of a signal, one would then go for x100 increased sensitivity. If a signal is seen, then the program would involve measuring muon to electron conversion rates as a function of the Z of the target nucleus – the rates will depend on the nature of the interaction: supersymmetric models vary among themselves, which are then different from Littlest Higgs or leptoquarks, etc. An ensemble of measurements from this experiment, $\mu^+ \to e^+ + \gamma$, and $\mu^+ \to e^+ + e^+ + e^-$ could pin down the nature of the new physics.

Summarizing, a new experiment, Mu2e, is being developed at Fermilab to measure the rate of muon to electron conversion with four orders of magnitude better precision than previous experiments. Any signal is a sign of new physics, and some new models predict a branching ratio just beyond the current limit. Muon to electron conversion is unique among cLFV muon interactions in its potential to go another two or more orders of magnitude in experimental sensitivity beyond Mu2e, and this will certainly be a key experiment in future pulsed proton source programs.