# Searching for Lepton Flavor Violation with the MECO Experiment at BNL

Michael Hebert*
*University of California, Irvine*

This paper motivates and describes the Muon-to-Electron COnversion (MECO) experiment proposed for the AGS at Brookhaven National Laboratory. The experiment seeks to detect coherent conversion of a muon to an electron in the field of a nucleus with a rate sensitivity of $2 \times 10^{-17}$. MECO will make use of a number of improvements to achieve this four order of magnitude increase in sensitivity over previous experiments. Numerous theoretical extensions of the Standard Model predict that an experiment of this sensitivity could observe a substantial lepton flavor violation signal in the charged sector.

The Muon to Electron COnversion (MECO) experiment [1, 2, 3] is designed to search for the coherent conversion of muons to electrons in the field of a nucleus with unprecedented sensitivity. The experiment is expected to achieve a rate sensitivity for muon conversion relative to that for muon capture on the same species of nucleus ($R_{\mu e} \equiv \Gamma(\mu^- N \to e^- N)/\Gamma(\mu^- N \to \nu N'))$ of about $2 \times 10^{-17}$. We know from observation that there is an additive quantum number associated with each type of lepton, the non-conservation of which is commonly referred to as lepton flavor violation (LFV). Although this quantum number is nearly exactly conserved there is no known fundamental gauge symmetry that requires this to be the case. Recently Super-Kamiokande has reported [4, 5, 6, 7] that $\nu_\mu$ appear to oscillate into some other neutrino species. This observation of LFV in the neutral sector can be accommodated within the Standard Model by postulating that neutrinos have mass and that they mix. However, the Standard Model so modified predicts that LFV among the charged leptons remains at a level well below that conceivably accessible by experiment. Hence, experiments that search for LFV in the charged sector constitute a search for the existence of fundamentally new physics.

Searches for LFV processes have been conducted since the discovery of the muon with ever-increasing sensitivity. In the case of muons effectively converting to electrons, for example in processes like $\mu \to e\gamma$ or $\mu^- N \to e^- N$, no signal has been seen and current upper limits are at the level of $10^{-11}$ to slightly below $10^{-12}$ as shown in Table I.

Also indicated in the table are the effective mass reaches achieved by each of these sensitive searches. The goal of the next round of experiments [1, 17] is to push the sensitivity to LFV processes to between $10^{-14}$ and $10^{-17}$, depending on the process. This corresponds to mass reaches in the thousands of TeV, and has lead to a renewed interest in LFV signatures for physics beyond the Standard Model. Essentially all such models naturally allow LFV, and the limits on LFV processes already place severe constraints on allowed models. Recent research in grand unified

Table I Experiments on lepton flavor violation: the current experimental limits, the change in generation number in the model of Cahn and Harari [8], the effective mass measured and the inferred limits on the mass.

| Process | Limit | ΔG | Measured | Mass Limit (TeV) |
|---|---|---|---|---|
| $K_L^0 \to \mu^\pm e^\mp$ [9, 10, 11] | $4.7 \times 10^{-12}$ | 0,2 | $m_H(g_W/g_H)/\cos\beta_{LU}$ | 150 |
| $K_L^0 \to \pi^0 \mu^\pm e^\mp$ [12] | $3.2 \times 10^{-10}$ | 0,2 | $m_H(g_W/g_H)/\cos\beta_{LU}$ | 37 |
| $K^+ \to \pi^+ \mu^+ e^-$ [13] | $2.1 \times 10^{-10}$ | 0 | $m_H(g_W/g_H)/\cos\beta_{LU}$ | 35 |
| $\mu^+ \to e^+ e^+ e^-$ [14] | $1.0 \times 10^{-12}$ | 1 | $\Delta(g_W/g_H)/(\cos\beta_{LL}\sin\beta_{LL})^{1/2}$ | 80 |
| $\mu^+ \to e^+ \gamma$ [15] | $1.2 \times 10^{-11}$ | 1 | $\Delta(g_W/g_H)/(\cos\beta_{LL}\sin\beta_{LL})^{1/2}$ | 21 |
| $\mu^- N \to e^- N$ [16] | $7.8 \times 10^{-13}$ | 1 | $m_H(g_W/g_H)/(\sin\beta_{LQ})^{1/2}$ | 340 |

*mhebert@uci.edu; http://meco.ps.uci.edu

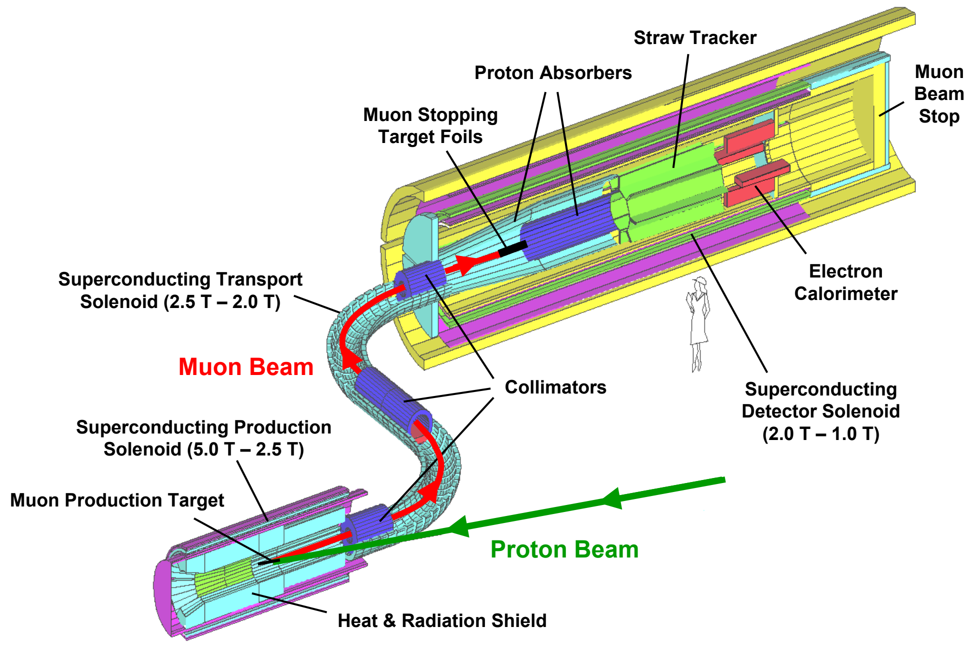


Figure 1: The proposed MECO experiment at the AGS.

supersymmetric models [18, 19, 20] has shown that LFV is expected in these models at a level that will be experimentally accessible: $10^{-15}$ in the case of $\mu^- N \to e^- N$ and $10^{-13}$ in the case of $\mu \to e\gamma$. The extent to which these predictions are robust is still under study.

The MECO experiment is extensively described in the original proposal to BNL [1], in the RSVP proposal [2], and in the MECO Draft Technical Proposal [3]; it is illustrated schematically in Figure 1. The goal of MECO is to improve upon the sensitivity of earlier experiments by a factor of ~10000. The new techniques that lead us to believe that such an improvement is possible are discussed below.

To reach the sensitivity goal, muon beam intensity must be increased 1000-fold over previous experiments. The plan is to achieve this through the combined effects of a very intense proton source, a high Z production target to increase pion yield, and a graded solenoidal field to maximize pion collection. The Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory will provide the intense ($4 \times 10^{13}$ protons/sec), but relatively low energy (8 GeV) proton beam. The beam will be pulsed to avoid backgrounds in which the putative conversion electron is detected in time coincidence with the arrival of a beam particle at the muon stopping target. The pulse interval is chosen to be 1.35 $\mu$s to approximately match the $\mu^-$ lifetime in aluminum. To produce this time structure the AGS will be operated with two of the nominal six RF-buckets filled. The beam will remain bunched during slow extraction. The conversion electron is detected in a ~700 ns time window between bunches when there is no beam in the detector region.

The total intensity requirement is modest by AGS standards, however the per bunch intensity is roughly a factor of two greater than that previously demonstrated in the machine. That intensity is presently limited by space charge effects during accumulation and by losses as the beam energy moves through transition. For MECO only a single booster transfer is required, reducing the accumulation time from 800 ms nominally to 133 ms and thereby reducing the space charge effects as well. The required beam energy of 8 GeV is below transition in the AGS. As a result it is believed that the AGS can reach the required per bunch intensity without significant hardware modification.

The proton beam is directed onto the production target that lies within a superconducting solenoid as shown in Figure 1. The field within the solenoid is graded axially such that the field strength increases along the path of the proton beam, which is opposite to the direction of the outgoing muon beam. Pions moving in the forward direction,but outside the graded magnet's loss cone (~30°),will be reflected by the higher field. They will be directed, along with backward-produced pions, toward the transport solenoid. A large fraction of the confined pions decay, producing muons that accelerate out of the low field region into the transport solenoid. The resulting efficiency is ∼.0025 stopped $\mu^-$ per incident proton.

The muon beam is transported within a combination of solenoids and sections of toroids. The curved transport solenoid exploits *curvature drift* to sign and momentum select the beam. It also serves to reduce the flux of neutrons and photons that are transported to the detector solenoid region by eliminating a line-of-sight path between the production target and the stopping target. Slowly propagating anti-protons, which are a potential source of background within the delayed detection time window, are stopped in a thin (120 $\mu$m) beryllium window within the central collimator of the transport solenoid.

The target in which the muons are stopped is situated in a graded solenoidal field and the conversion electron detectors are displaced several meters downstream of the target to a region of uniform field. The graded field varies from 2 T at the solenoid entrance to 1 T in the vicinity of the detectors. Electrons that are initially moving upstream encounter an increasing field and reflect back toward the detectors, resulting in large acceptance. Electrons with 105 MeV/c total momentum that are produced upstream of the graded field cannot have transverse momentum greater than 75 MeV/c in the detector region, thereby eliminating many potential sources of background. By displacing the detectors well downstream of the stopping target, the solid angle for neutrons and photons produced in the target to reach the detectors is greatly reduced. Further, protons produced in the stopping target can be attenuated with absorbers placed between the stopping target and detectors.

The signal for the experiment is simply a 105 MeV electron originating in the muon stopping target and detected within the 700 ns active time window. The single particle final state eliminates accidental coincidence backgrounds at high rates that are a potential problem when searching in other LFV channels. Background sources of 105 MeV electrons are heavily suppressed. The primary background source, muon decay in nuclear orbit (DIO), has an endpoint energy of 105 MeV. The rate of DIO electrons, however, is a steep (fifth power) function of the energy below the endpoint, thus this background can be controlled by precise measurement of the energies of conversion electron candidates.

The conversion electron detectors are illustrated in Figure 1. The tracking detector shown consists of approximately 3000 5 mm diameter straw tubes oriented along the axis of the solenoid. Axial hit information is provided by capacitively coupled cathode strips outside the straws. An octagonal detector with vanes extending radially outward yields good acceptance according to GEANT simulations.

The electron calorimeter shown in the figure serves as the primary hardware trigger for the experiment and also to confirm the electron's trajectory and energy as measured in the straws. This detector will be composed of approximately 2000 scintillating crystals arranged in four planes of detectors. Not shown in Figure 1 is a cosmic ray shield consisting of a double layer of scintillation detectors completely surrounding the detector solenoid, and extensive passive shielding.

GEANT simulation of the detector system [2] has determined the electron energy resolution as ∼900 keV (FWHM), the uncertainty coming largely from fluctuations in the energy lost in the target and from multiple scattering. With that resolution, these studies predict that the contribution of DIO background in the region above 103.6 MeV to be one twentieth the signal, for $R_{\mu e} = 10^{-16}$. When all sources are considered, the total background for this value of $R_{\mu e}$ is 0.45 events, while the expected signal is 5 events.

At present MECO is a collaboration of 34 physicists from 10 institutions with several additional groups having expressed an interest in participating. The experiment has been approved by the National Science Board and is anticipating construction funding to commence in FY03. Funding for MECO and the KOPIO experiment also at the AGS will be provided via a Major Research Equipment grant from the National Science Foundation called the Rare Symmetry Violating Processes (RSVP) program. If construction begins on schedule, MECO is expecting to take its first beam early in 2006 and begin production running late in that year.

## References

[1] M. Bachman *et al.*, *A search for $\mu^- n \to e^- n$ with sensitivity below* $10^{-16}$ (1997), research proposal to Brookhaven National Laboratory.

[2] *Rare symmetry violating processes* (1999), http://meco.ps.uci.edu.
[3] *Draft meco technical proposal* (2001), http://meco.ps.uci.edu.
[4] Y. Fukuda *et al.*, Phys. Lett. B **436**, 33 (1998).
[5] Y. Fukuda *et al.*, Phys. Lett. B **433**, 9 (1998).
[6] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
[7] Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2644 (1999).
[8] R. N. Cahn and H. Harari, Nucl. Phys. **B176**, 135 (1980).
[9] D. Ambrose *et al.*, Phys. Rev. Lett. **81**(26), 5734 (1998).
[10] K. Arisaka *et al.*, Phys. Rev. Lett. **70**(8), 1049 (1993).
[11] T. Akagi *et al.*, Phys. Rev. Lett. **67**, 2614 (1991).
[12] P. Krolak *et al.*, Phys. Lett. B **320**(3-4), 407 (1994).
[13] R. Appel *et al.*, Phys. Rev. Lett. **85**, 2450 (2000).
[14] U. Bellgardt *et al.*, Nucl. Phys. **B299**, 1 (1988).
[15] M. L. Brooks *et al.*, Phys. Rev. Lett. **83**, 1521 (1999).
[16] T. W. Donnelly, ed., *Proceedings of the Sixth Conference on the Intersections of Particle and Nuclear Physics*, New York (1997), American Institute of Physics.
[17] L. Barkov *et al.*, *Search for* $\mu^+ \to e^+ \gamma$ *Down to* $10^{-14}$ *Branching Ratio* (1999), research proposal to Paul Scherrer Institut.
[18] R. Barbieri and L. J. Hall, Phys. Lett. **B338**, 212 (1994).
[19] R. Barbieri, L. Hall, and A. Strumia, Nucl. Phys. **B445**, 219 (1995), hep-ph/9501334.
[20] J. Hisano *et al.*, Phys. Lett. **B391**, 341 (1997).