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Muon to Electron Conversion: Experimental Status in Japan and the US

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A description is given of two experiments currently being developed to measure muon to electron conversion. The Mu2e and COMET experiments are being prepared at Fermilab and J-PARC, respectively. Muon to electron conversion, $\mu^- N \rightarrow e^- N$, is an example of charged lepton flavour violation (cLFV), where a muon converts into an electron with no accompanying neutrinos in the near field of a nucleus; conservation of each of electron and muon lepton number is violated. cLFV has never been observed experimentally, but readily appears in most speculative models beyond the Standard Model. A measurement with improved sensitivity will either see a signal indicating new physics or place strong constraints on most proposed extensions to the Standard Model. The two proposed experiments have set similar goals of $R_{\mu e} < 7 \times 10^{-17}$ (90% C.L.), an improvement on the existing experimental limit by four orders of magnitude.

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1. Introduction

In the Standard Model (SM), the leptons, which are those particles that do not interact via the strong interaction, are grouped into three generations: electron and electron neutrino, muon and muon neutrino, and tau and tau neutrino (likewise the strongly-interacting quarks have three generations). Although this pattern is a major feature of the SM, no underlying symmetry has yet been discovered that explains it. Given its central role in theory, there are extensive experimental efforts under way to try to elucidate the source of this structure. In particular, one of the properties of leptons, lepton number conservation, has been under investigation in many interaction channels over the past 50 years. The number of particles in a given lepton generation is observed to be conserved in any interaction, the sole exception being the observed oscillation of neutrinos from one generation to another. There have been many experimental searches for *charged* lepton violation (cLFV), for example involving the muon interactions $\mu^- N \to e^- N$, $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$, so far with null results. Yet most models of new physics naturally allow cLFV, so that every new experimental limit leads to ever tighter restrictions on these models.

Two new experiments, the Mu2e experiment at Fermilab in the USA and the COMET experiment at J-PARC in Japan, are being prepared to measure the rate of muon to electron conversion in aluminum with goals to improve the sensitivity over past experiments by roughly four orders of magnitude. Muon to electron conversion is the neutrinoless conversion of a muon to electron in the near field of a nucleus, $\mu^- N \to e^- N$. Note that the presence of the nucleus is required to conserve energy and momentum. As mentioned, this is an example of a charged lepton flavor violating (cLFV) reaction: the number of muon leptons goes from one to zero and the number of electron leptons goes from zero to one. Contrast this with the normal muon decay mode, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$, where both lepton numbers are conserved- total muon lepton number of one (μ^-, ν_μ) and total electron number of zero $(0, e^-\bar{\nu}_\mu)$ in each of the initial and final states. While the primary emphasis of this note is on $\mu^- N \to e^- N$, we will also refer to the other two related members of the cLFV 'trio', $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$.

Since neutrinos *do* violate the lepton number conservation rule, in an extended version of the SM in which one accounts empirically for neutrino oscillations, it is possible to draw a loop diagram that leads to cLFV in the $\mu^+ \to e^+\gamma$ decay, see Figure 1. The branching ratio for this reaction however is predicted to be ~10^{-54}, far below any foreseeable experimental sensitivity, and similarly small branching ratios are found for $\mu^- N \to e^- N$ and $\mu^+ \to e^+e^+e^-$. One can conclude that in searches for cLFV there will be no SM background and that any signal is a definite sign of new physics.

The diagrams of contributions to muon to electron conversion from a selection of postulated new physics models are shown in Figure 2. The top left diagram depicts a SUSY contribution, with the exchange of virtual sleptons and a gaugino, and a photon line which goes from the slepton to a quark in the nucleus. The corresponding diagram for $\mu^+ \to e^+\gamma$ is obtained by simply removing the quark line, and the diagram for $\mu^+ \to e^+e^+e^-$ is obtained by replacing the quark line with an electron line. The addition of these lines make both $\mu^+ \to e^+e^+e^-$ and $\mu^-N \to e^-N$ less sensitive to cLFV than $\mu^+ \to e^+\gamma$ by approximately a factor of roughly $\alpha/2$ to $\alpha/3$, where α is the fine structure constant. In the case of $\mu^-N \to e^-N$ this is more than compensated by the proposed experimental sensitivity compared to $\mu^+ \to e^+\gamma$.

Note that in Figure 2, there are also contributions from a quark-lepton contact diagram and from diagrams that include exchanges of heavy particles (e.g. leptoquark, Z') with a quark. There is no quark available at tree level in the case of $\mu^+ \to e^+\gamma$ and it is largely insensitive to these types of interactions. Therefore $\mu^-N \to e^-N$ is sensitive to a broader class of new physics effects. Likewise, $\mu^+ \to e^+e^+e^-$ could have tree level contributions from the exchanges of heavy particles by replacing the quark line in selected diagrams with an electron line, for example the case of Z' exchange. It is clear that if a signal is seen in one of these three reactions, the other reactions will offer complimentary information on cLFV that will help sort out its source.

Some of the tightest constraints on new models of physics come from the limits imposed by the failure to observe cLFV. The reader is referred to the literature[1].

2. Description of Experiments

The experimental approach to $\mu^-N \to e^-N$ begins with protons striking a primary target and producing pions. The pions decay to muons. Low energy negative muons are directed by a beam line to a suitable thin target material where they stop; aluminum has been chosen as the target material for both Mu2e and COMET. The stopped muons are spontaneously captured into atomic orbit around the nucleus and promptly cascade to the 1S state. The Bohr radius of the muon is only 20 fm, thus there is significant overlap between the nuclear and muonic wavefunctions, making exchanges of heavy particles possible. A search is then made for a monoenergetic electron, 105 MeV in the case of aluminum. The primary modes of interaction of the muon in this state is either decay in atomic orbit (DIO), $\mu^-N \to Ne^-\ \nu_\mu\bar{\nu}_e$ or capture on the nucleus $\mu^- + {}^A_Z N \to {}^A_{Z-1} N' + \nu_\mu$. The muon lifetime in the atomic bound state is reduced by the captures from 2.2 μsec for free muons to 864 ns. The DIO electron energy can reach all the way up to the conversion electron energy at 105 MeV because the nucleus can absorb some energy and momentum; contrast this with the decay of a free muon, where the endpoint energy is 53.8 MeV. The DIO electrons can pose a background threat to the conversion electron measurement, but fortunately the DIO branching ratio near the conversion energy is quite small and falling rapidly as the energy approaches the endpoint. The DIO background in the vicinity of the conversion electron energy can be eliminated with sufficiently good electron energy resolution (~1 MeV FWHM).

The current best limit on $\mu^- N \to e^- N$ comes from the SINDRUM II experiment at PSI [2], $R_{\mu e} = \dfrac{\mu^- N \to e^- N}{\mu^- N \to N' \nu_\mu (capture)} < 7 \times 10^{-13}$ (90% C.L.). Mu2e and COMET both plan sensitivity goals of $7 \text{x} 10^{-17}$, using about $4 \text{x} 10^{20}$ delivered protons and approximately $1 \text{x} 10^{18}$ stopped muons- four orders of magnitude sensitivity improvement over the SINDRUM II measurement.

There are several planned improvements in experimental designs that will help achieve this goal. We list a few here.

1) The proton beam will be pulsed in order to eliminate radiative pion capture and other prompt backgrounds. Negative pions, which generally accompany muons in the beam line, can stop in the target and immediately undergo radiative pion capture (RPC), $\pi^- N \to N' \gamma$. About 2% of the time the photon has an energy between 55 and 139 MeV. If the photon energy is above 105 MeV, it can produce a 105 MeV electron via pair production in the target. This electron is indistinguishable from a conversion electron, and presents a serious potential background. In most previous experiments, a continuous beam was used. To control the RPC background, a veto counter was placed in the beam, and any conversion electron candidate in time coincidence with an incoming beam particle was rejected. Such an arrangement places a limitation on the intensity of the incoming beam, and is impractical for the very high beam rates required for Mu2e or COMET sensitivity goals. Instead, the proposed new approaches use a pulsed proton beams. A narrow pulse of protons (<200 ns) impinges on the production target. Search for conversion electrons is delayed until almost all the pions have interacted or decayed (estimated from simulations to be about 700 ns). The search continues until the next protons pulse (pulse spacing 1700 ns for Mu2e). Aluminum is well-suited as a target material because the muon's lifetime is long enough that a large number of muonic atoms survive after the 700 ns delay (Z of the nucleus not too large), yet there is still substantial overlap between the nuclear and muonic wavefunctions (Z not too small) in order to maximize the potential conversion rate.
2) New solenoidal beam lines are being developed that have a much better efficiency of collecting and transporting low energy muons to the stopping target than conventional beam lines.
3) The pulsed proton beams will be high intensity.
4) The magnetic tracking detectors will produce excellent electron energy resolution (<1 MeV at 105 MeV).

The principles guiding the Mu2e and COMET muon beamline designs are similar. Here we describe the proposed Mu2e beamline in more detail. The Mu2e beamline consists of three superconducting solenoids connected in series, a 4 m long x 1.5 m diameter Production Solenoid (PS), a 13 m long x 50 cm diameter Transport Solenoid (TS) and an 11 m long x 2 m diameter Detector Solenoid (DS) (see Figure 3). This beamline system will deliver about 0.002

stopped muons per 8 GeV incident proton. Protons from the upstream direction strike a tungsten production target near the center the PS, produce pions that decay into muons, and some of the muons and pions are captured in helical orbits, spiral downstream, and enter the TS. The PS field is graded from 4.6 to 2.5 Tesla upstream to downstream which causes the z component of momentum of the spiraling particles to continuously increase in the downstream direction, thereby improving the efficiency of capture of particles into the TS. A thick bronze shield protects the coils of the PS from heat and ionizing radiation emanating from the production target. The S-shape of the TS removes any line of sight photons and neutrons traveling from the production target to the detector region. In the first toroid section of the TS, spiraling negative particles drift upward while positive particles drift downward. The distance of the vertical drift depends on the momentum and pitch of the helix. An off-center collimator at the middle of the TS preferentially passes low momentum negative muons, suppressing positive particles and high momentum negative particles. The second toroid section, curving in the opposite direction from the first, re-centers the beam in the solenoid.

The particles then continue in helical paths into the DS. In the upstream 4 m of the DS, the magnetic field grades linearly from 2 T to 1 T, and this is followed by a constant 1 T field in the detector region (see Figure 3). The stopping target is placed half-way through the gradient and consists of 17 disks of 99.99% Al, each 0.2 mm thick spaced at 5 cm intervals. Conversion electron candidates that are initially spiraling upstream can be reflected by the gradient field back toward the detectors, increasing acceptance. This also helps to eliminate background due to particles coming down the beamline- regardless of their initial pitches at the entrance to the DS, their pitches will be increased beyond that for acceptable conversion electron candidates emanating from the target when they arrive at the end of the gradient region. Potential conversion events pass through the tracker and then stop in the calorimeter. The detectors are displaced downstream from the stopping target in order to reduce the flux of neutrons and gammas from the muon capture reactions in the target. Both the tracker and calorimeter are hollow on the inside so that most of the copious flux of low energy DIO electrons have insufficient transverse momenta to strike the detectors electrons, and spiral harmlessly to a beam dump downstream.

Mu2e has received Fermilab approval and has achieved CD1 approval from the US DOE, which enables funding for much more detailed design of the experiment. Substantial solenoid and proton beam preliminary design work has been completed, and extensive background and signal simulations, including hit-level tracking simulations, have been done. Current plans have Mu2e commencing data taking in 2019, with the schedule mainly dictated by the time required to design and construct the muon and proton beam lines.

COMET proposes to use a C-shape rather than the S-shape transport solenoid proposed by Mu2e. A vertical dipole magnetic field is added to the toroidal sections in order to center the desired low momentum negative muons in the transport solenoid. The result is in slightly improved momentum separation in the beam but slightly lower muon flux, compared the S-shape. A 180 degree toroid is added between the stopping target and the detectors, reducing the flux of backgrounds due to low energy particles from the beam line and stopping target. The 105 MeV electrons are centered in the toroid by means of vertical magnetic dipole field. COMET has recently revised their schedule so that construction occurs in two phases. In phase

1, the proton beam line, production solenoid, and first bend of the transport solenoid are constructed. The stopping target is surrounded by a cylindrical magnetic spectrometer, similar to the SINDRUM II experiment. Phase 1 would have an intermediate sensitivity goal of about 1×10^{-14} and will provide information on backgrounds for stage 2. Phase 1 is expected to commence data taking in about 5 years, then followed by the full implementation in Phase 2.

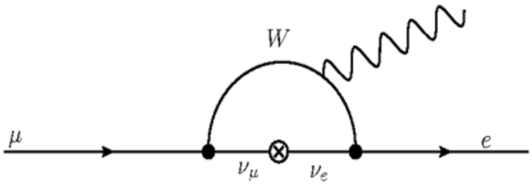

Figure 1. Contribution to cLFV in $\mu \rightarrow e\gamma$ in the Standard Model, which has been modified to account for neutrino oscillations.

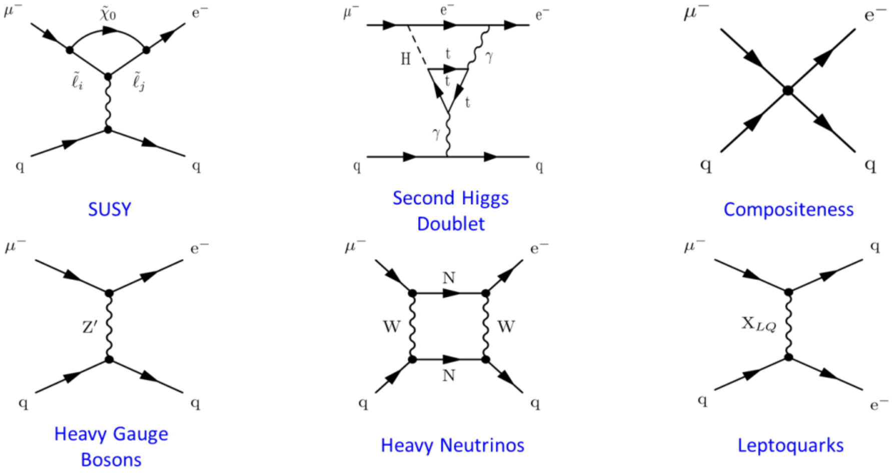

Figure 2. Possible contributions to muon to electron conversion in selected new physics models. Credit: W. Marciano.

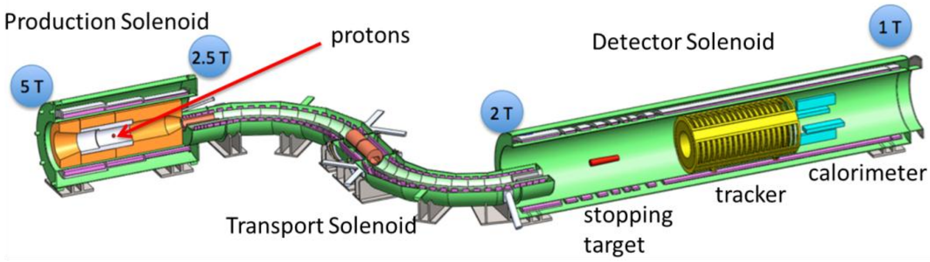

Figure 3. Mu2e solenoidal muon beamline.

References

[1] See for example: L. Calibbi, A Faccia, A. Masiero, S. Vempati, hep-ph/0605139; M. Blanke, A.J. Buras, B. Duling, A. Foschenrieder, JHEP 0705, 013(2007); C. Albrecht and M. Chen, PRD D77, 113010 (2005).

[2] W. Bertl et al., Eur. Phys. J. C47, 337(2006).