The Mu2e Experiment at Fermilab: $\mu^- N \rightarrow e^- N$

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http://mu2e.fnal.gov

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ABSTRACT

Mu2e will search for coherent, neutrino-less conversion of muons into electrons in the field of a nucleus to a few parts in 10^{-17}, a sensitivity improvement of a factor of 10,000 over existing limits. Muon-Electron conversion provides unique windows into new physics inaccessible to other lepton flavor violation searches and probes up to mass scales ~ 10,000 TeV, far beyond the reach of present or planned high energy colliders. The Mu2e collaboration has proposed an experiment to search for muon to electron conversion to be mounted at Fermilab. If no events are seen in the signal window, it will set an upper limit of:

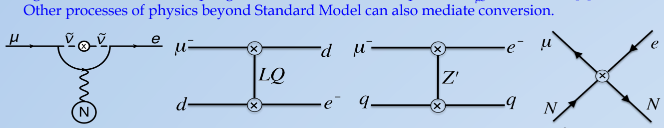
$$R_{\mu e} = \frac{\Gamma\left(\mu^- + (A,Z) \rightarrow e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \rightarrow \text{capture}\right)} \leq 6 \times 10^{-17} \text{ @ } 90\%CL$$

If the present Fermilab schedule is maintained, Mu2e will start data taking in 2019.

Muon to electron conversion

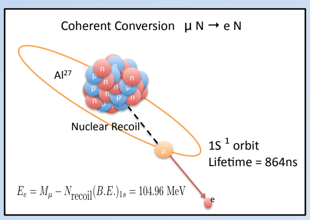
Charged Lepton Flavor Violation (CLFV) in the Standard Model can occur only through the intermediate mixing of massive neutrinos. The rate depends on the neutrino mass splitting and couplings and the expected value is $B(\mu \rightarrow e\gamma) \approx 10^{-52}$

If SUSY exists, it can mediate electron conversion via a diagram such as one of those shown in figure. For masses and couplings accessible at LHC, SUSY predicts $R_{\mu e}$ of order 10^{-15} [1].
Other processes of physics beyond Standard Model can also mediate conversion.



SUSY magnetic moment diagram — Lepto-quark exchange — Z′ exchange — Effective contact interaction

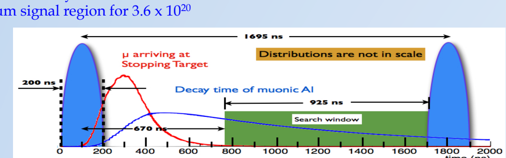
In the 2-body final state (monoenergetic electron + intact unobserved nucleus) almost all of the kinetic energy is carried away by the electron. The energy is given by the muon mass less a correction for the binding energy and the small part of the momentum carried by the nucleus. For the Al nucleus case, the electron energy is 104.96 MeV, the lifetime of the bound state is 864 ns.



The backgrounds

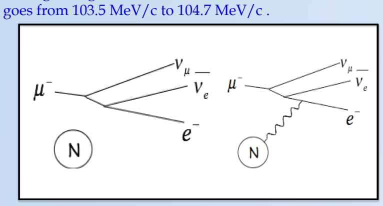
Radiative Pion Capture
Given by the negative pions stopped on the Al targets:
$\pi^- N \rightarrow \gamma N^{Z-1}$, $\gamma \rightarrow e^+e^-$
About 2×10^{-4} decay electrons are in the momentum signal region for 3.6×10^{20}

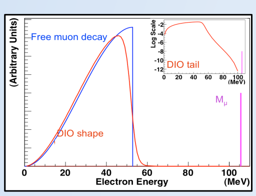
Prompt beam related background
It is suppressed by a delayed “live” window which starts about 670 ns after the beam pulse.



Muon nuclear capture and Decay in Orbit (DIO)
The muon capture by Al atoms has two dominant final states:
- muon nuclear capture, about 60% of the time, which ends up in nucleons and photons
- muon DIO, about 40% of the time

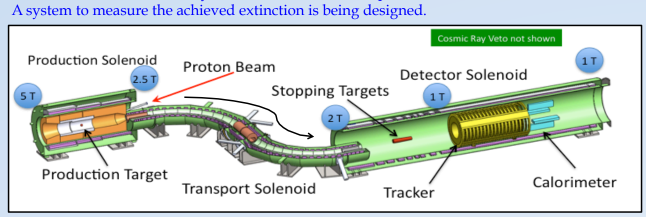
The irreducible physics background to muon to electron conversion is the high energy tail of DIO[2].
An excellent momentum resolution can suppress this background (designed is 150 KeV/c).
The signal region of reconstructed momentum in which we search for conversion electrons goes from 103.5 MeV/c to 104.7 MeV/c .





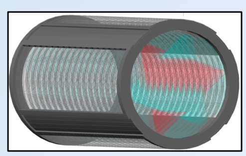
Beam and solenoids

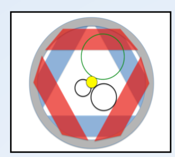
An 8 GeV proton beam strikes a tungsten production target in the production solenoid (PS) to produce pions that decay into muons.
A system of graded solenoids and collimators collect back-scattered muons and deliver them to the stopping target, a set of thin aluminum foils.
The S-bend in the transport solenoid (TS) ensures that neutrals from the PS do not have a direct line of sight to the stopping targets; it also does charge and momentum selection on the muon beam.
DIO and conversion electrons from the stopping targets are transported in a graded magnetic field to the spectrometer which consists of a tracker and a calorimeter.
The graded magnetic field recovers conversion electrons headed upstream of the muon beam, and also maximize the acceptance sweeping lower momentum DIO electrons out of the acceptance of the detector (see section below).
Fewer than 10^{-10} protons are required to arrive between the beam pulses: a conceptual design exists for a beam extinction system that can meet the requirements.
A system to measure the achieved extinction is being designed.

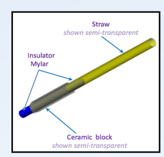


Tracker and calorimeter

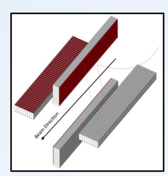
Tracker is made by 18 parallel stations (left figure). Each station is formed by placing two planes back to back, with one rotated by 30 degrees relative to the other.
The plane (middle figure) is made by 6 panels placed in two different surfaces (pink and blue in the picture). Each of the panels consists of 100 straw tubes, arranged in two layers; each straw (right figure) has a diameter of 5 mm. Pink panels are mounted on the front of the support structure, blue panels are mounted on the rear. The uninstrumented region at small radius allows the overwhelming majority of DIO electrons to pass through without registering a hit (see circles in the middle figure). Only about 10^{-10} of all the DIO are seen, in order to keep the background rates at a very low level.







The calorimeter is composed by 4 vanes (left figure). Each of them is a matrix of LYSO crystals (right figure), each 3x3x11 cm^3, arranged in a grid of 11 crystals radially by 44 crystals longitudinally. Electrons spiral in the sense that they will hit the red faces shown in figure. An APD based readout is housed on the opposite face.



Expected background events for 3.6×10^{20} protons on target will be 0.41±0.08
Most important sources:
Muon DIO (0.22±0.06)
Cosmic Rays (0.050±0.025)
π decay-in-flight (0.0030±0.0015)
Anti-protons from beam (0.100 ± 0.035)
Radiative π capture on foils (0.030 ± 0.007)
Muons decaying on flight (0.010 ± 0.003)
Beam electrons (0.0006 ± 0.0003)

Sensitivity for 3.6×10^{20} protons
No new physics case:
set a limit $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
New physics case for $R_{\mu e} \approx 10^{-15}$:
O(40) events on a background < 0.3 events

Future: Need Fermilab’s Project X to increase muon statistics: if we see a signal, we will vary Z to study new physics; if not, we will use the statistics to reduce the limit as low as $R_{\mu e}$<O(10^{-18})

References:

1. M. Raidal et al., Eur.Phys.J.C57:13-182,2008.
2. A. Czarnecki et al., Phys. Rev. D84(2011) 013006.