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

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Introduction

Within the Standard Model, muons decay in a way that almost perfectly conserves lepton family number; the standard model branching fractions to final states that violate lepton family number are much too small to be observed with present technology. Therefore any observation of a muon decay that violates lepton family number is direct evidence for physics beyond the Standard Model. One of the most striking of these decay modes cannot occur for free muons but may occur when negative muons are bound to an atomic nucleus, forming a muonic atom: coherent, neutrino-less muon to electron conversion in the Coulomb field of a nucleus. In this process, the final state is a mono-energetic electron plus an unobserved, recoiling, intact nucleus. The Mu2e collaboration has proposed an experiment to search for muon to electron conversion; this experiment is to be mounted at Fermilab and, if no events are seen in the signal window, will set an upper limit of:

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + (A,Z) \rightarrow e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \rightarrow e^- + (A,Z-1)\right)} \leq 6 \times 10^{-17} \ @\ 90\%\ CL$$

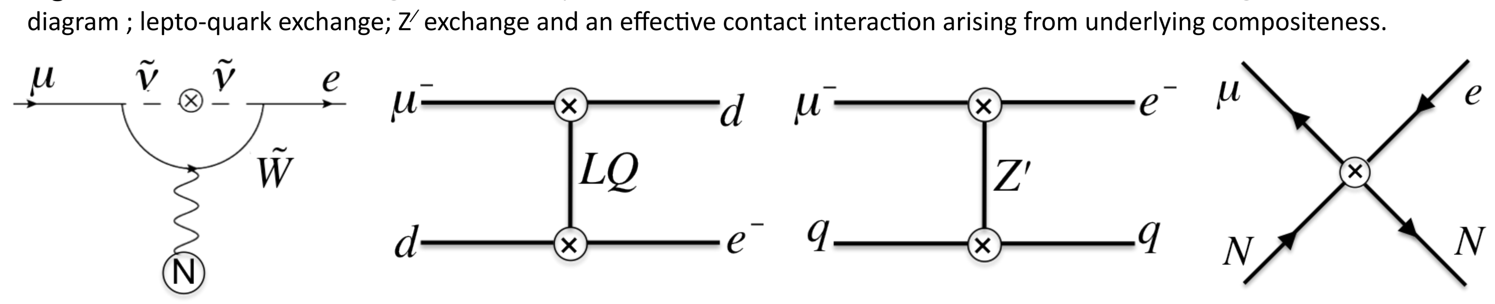
This sensitivity is 4 orders of magnitude better than the previous best experiment and implies a sensitivity to new particles with masses up to 10,000 TeV, far beyond the range that is directly accessible at the LHC. If the present Fermilab schedule is maintained, Mu2e will start data taking in 2018.

The Physics of Muon to Electron Conversion

In muon to electron conversion the initial state is a muonic atom, a state that has two dominant decay modes: muon nuclear capture and muon decay in orbit (DIO). For the Al nucleus, which will be used in Mu2e, muon nuclear capture occurs about 60% of the time while DIO occurs about 40% of the time; the lifetime of this bound state is, therefore, about 40% of the free muon lifetime, 864 ns. The irreducible physics background to muon to electron conversion is the high energy tail of DIO; this will be discussed in more detail below.

If SUSY exists, it can mediate muon to electron conversion via a diagram such as one of those shown in Figure 1. For masses and couplings that are accessible at the LHC, SUSY predicts Rμe of order 10^{-15}, for which Mu2e would observe about 40 events on a background of less than 0.3 events; this event yield assumes a run with 3.6×10^{20} protons on target (POT). Other sorts of physics beyond the standard model can also mediate conversion: Lepto-quark exchange, Z′ exchange and interactions arising from underlying compositeness. See reference [1] for details of these and related processes. At its design sensitivity, Mu2e is sensitive to intermediate states that have masses up to O(10,000 TeV).

Figure 1: Several classes of diagrams that can produce muon to electron conversion: a SUSY mediated magnetic moment diagram ; lepto-quark exchange; Z′ exchange and an effective contact interaction arising from underlying compositeness.



The above diagrams lead to a 2-body final state, an electron recoiling against an intact nucleus. Because of the large mass ratio, essentially all of the kinetic energy is carried away by the electron; the energy of the electron is the muon mass less a correction for the binding energy of the K-shell and a very small correction for the momentum carried by the recoiling nucleus. For the case of an Al nucleus, the energy of a conversion electron is 104.97 MeV.

As illustrated in Figure 2, muon decay in orbit is described by free muon decay plus radiative corrections from the exchange of a virtual photon between the nucleus and the outgoing electron. In Figure 3, the red curve shows the predicted lab frame energy spectrum for DIO electrons [2][3]. For reference, the magenta line marks the muon mass and the blue curve shows the Michel spectrum, which has a hard endpoint at half of the muon mass. The main difference between the two spectra is that the DIO energy spectrum has a long tail that extends far beyond the endpoint of the Michel spectrum; this tail is seen better on a log scale in the inset. The end point of the DIO energy spectrum occurs when the two neutrinos are at rest, in which case, ignoring neutrino masses, the final state is identical to that of muon to electron conversion: an electron recoiling against an intact, unobserved nucleus. Ignoring neutrino masses, the endpoint energy of the DIO energy spectrum is identical to the energy of a conversion electron. They key to suppressing this irreducible background is excellent energy resolution.

Figure 2: Diagrams for muon decay in orbit (DIO)

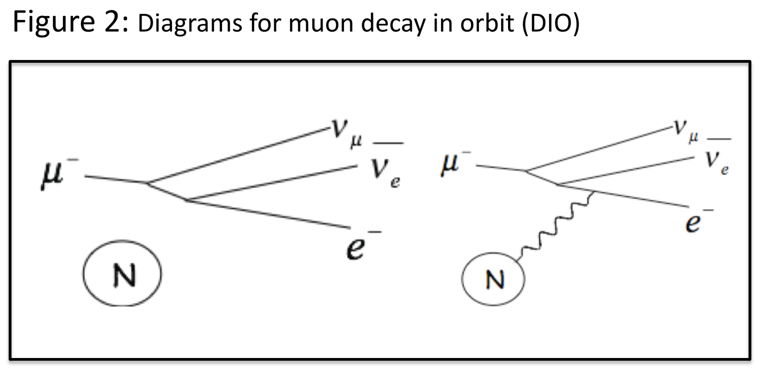
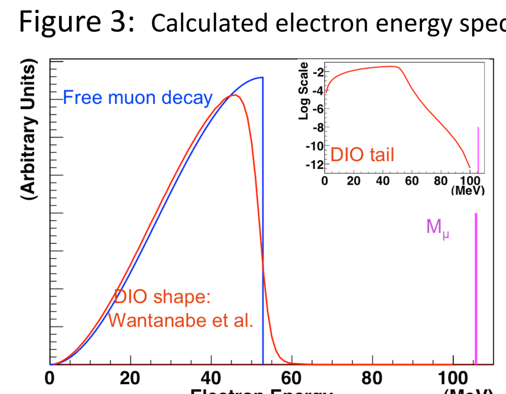


Figure 3: Calculated electron energy spectrum for DIO



A Cartoon of The Experiment

The Mu2e muon beam is very impure and many background processes are initiated by the numerous non-muons that arrive in-time with the muon beam. However all of these processes lead to prompt backgrounds; to defeat these backgrounds Mu2e simply waits for them to decay away. This is possible because the lifetime of muonic aluminium is long compared to the time structure of the prompt backgrounds. There is now enough information to sketch a cartoon of the Mu2e technique:

1) Make a low momentum muon beam.
2) Shoot it at target of many thin Al foils.
3) Some muons will range out in the first foil, some in the next foil, and so on.
4) When a muon ranges out, it will be captured to form a muonic atom.
5) Wait until the prompt backgrounds decay away.
6) Measure the energy spectrum of electrons that escape the foils.
7) Observe the shape of the electron energy spectrum near the DIO endpoint.
8) Is there an excess at the endpoint energy?

Why use many thin foils? Each foil must be thin in order to minimize the variation in energy loss as DIO and conversion electrons leave the foil in which they were born. But one thin foil will not stop enough muons. Therefore Mu2e uses many foils; the detailed optimization of the number, position and shape of foils is underway.

When a muonic atom is formed, the muon cascades to the K-shell, emitting characteristic X-rays. Mu2e will measure this X-ray spectrum to determine the denominator of the measured ratio.

The Mu2e Muon Beamline and the Detector

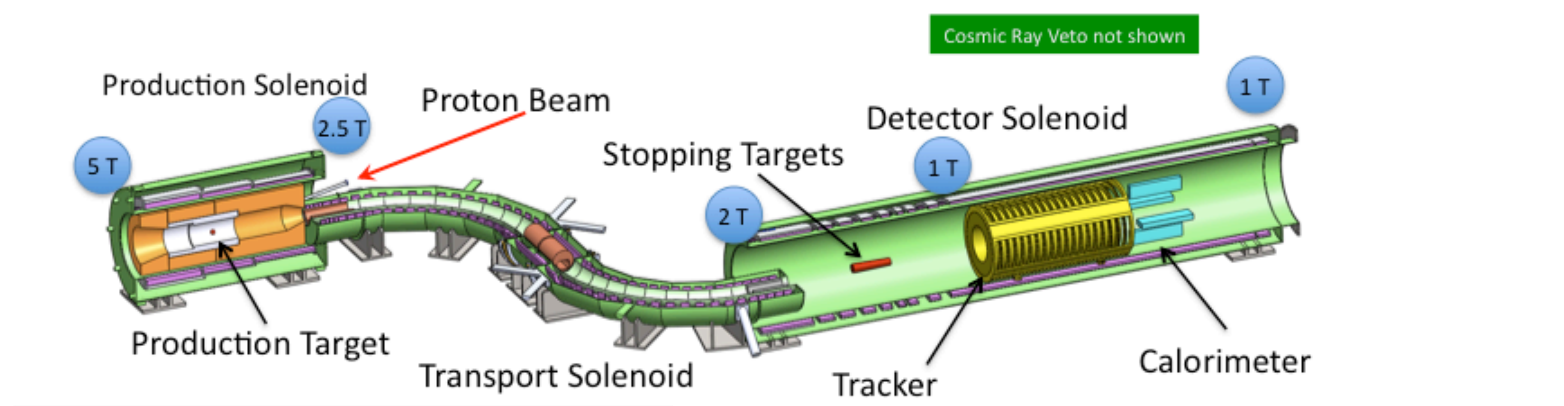


Figure 5: Time structure of one cycle of the muon beamline.

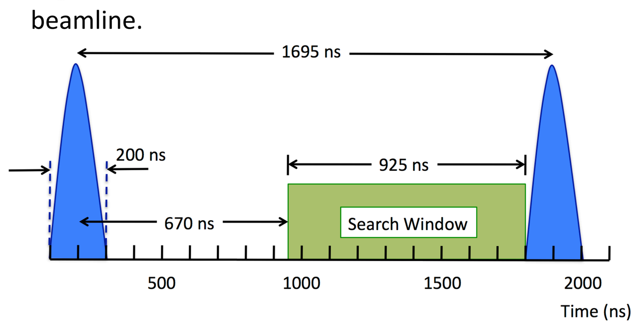


Figure 4: The Mu2e muon beamline showing the positions of the primary proton beam, the three solenoids, the production target, the stopping targets, and the detectors. The coral coloured insets in the TS are the collimators that define the aperture. The figure also shows the grading of the magnetic field strength; the blue bubbles give values of B_z. The grading in the PS and DS forms magnetic mirrors that enhance the yields of muons (PS) and conversion electrons (DS). The grading in the TS helps to reduce late arriving beam particles.

The Fermilab accelerator complex will deliver an 8 GeV proton beam onto a gold production target; interactions in the target produce pions that subsequently decay to muons. A system of graded solenoids and collimators forms a muon beamline, shown in Figure 4, that collects back-scattered muons and delivers them to the stopping target, a set of thin aluminium foils. A magnetic mirror in the PS increases the efficiency to collect muons. The S-bend in the TS ensures that neutrals from the production target do not have a direct line of sight to the stopping targets. DIO and conversion electrons from the stopping targets are transported to the spectrometer in a graded magnetic field; a second magnetic mirror increases the efficiency to collect electrons near the conversion energy. The momentum of these electrons is measured, with a resolution of about 150 keV/c , in a tracker; a calorimeter gives an independent measurement of position and energy. The calorimeter has poorer energy resolution than does the tracker but it helps to reject backgrounds arising from badly reconstructed tracks. The solenoid system is both the cost driver and the schedule driver for Mu2e.

The timing of one cycle of the muon beamline is illustrated in Figure 5. The Fermilab accelerator complex will deliver one bunch of about 10^7 protons onto the production target every 1695 ns; this time is set by the rotational period of the existing anti-proton debuncher ring, which will be repurposed for Mu2e. The proton pulse will have a full half width of about 100 ns. Mu2e will wait about 670 ns following the end of the proton pulse to allow prompt backgrounds to decay. This leaves a 925 ns live window during which DIO and conversion electrons will be measured. For Mu2e to achieve its target background levels, it is critical that, for every proton in the beam pulse, fewer than 10^{-10} protons arrive between pulses. A conceptual design exists for a beam extinction system that can meet this requirement and a system to measure the achieved extinction is being designed.

The Mu2e design includes a free running DAQ system that will record zero-suppressed data from all channels for each cycle of the muon beamline. This will be sent to a software trigger that will identify events that contain reconstructable tracks; these events will be written to tape for detailed offline analysis. Various triggered modes are also envisaged for calibration and other dedicated studies.

Figure 7 shows one plane in the tracking system. The grey ring shows support structure that is outside of the fiducial volume; the axis of the magnetic field is into the page. Each of the pink and blue panels represents 100 straw tubes, arranged in two layers; each straw has a diameter of 5 mm. The straws run parallel to the long axis of the trapezoids and the two layers are arranged out of the page. The pink panels are mounted on the front of the support structure, while the blue panels are mounted on the rear. A tracker station is formed by placing two planes back to back, with one plane rotated by 30 degrees relative to the other. The full tracking system is comprised of 18 stations, as shown in Figure 8. The design momentum resolution is about 150 keV/c.

Figure 9 shows the calorimeter, arranged in 4 vanes. Each vane is a matrix of LYSO crystals, each 3x3x13 cm^3, arranged in a grid of 12 crystals radially by 44 crystals longitudinally. Electrons spiral in the sense that they will hit the red faces shown in Figure 9. An APD based readout package is housed on the opposite face. The empty space in the middle of the tracker and the calorimeter allows all DIO electrons with $p_T <$ 55 MeV to pass through without registering a hit.

Figure 7: One plane in the tracking system.

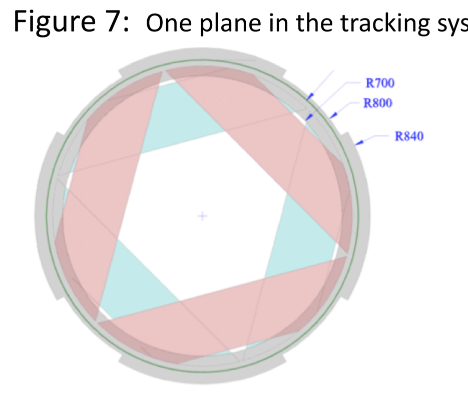


Figure 8: The 18 station tracking system.

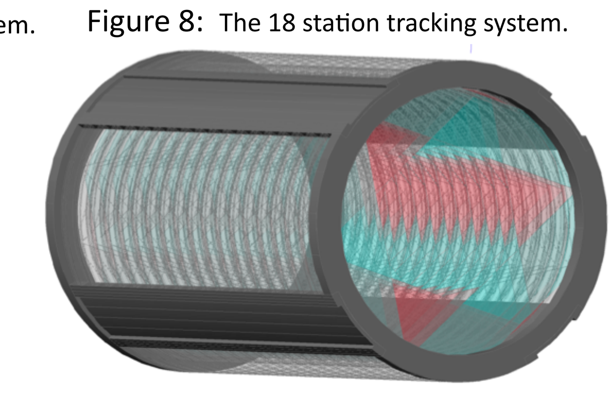
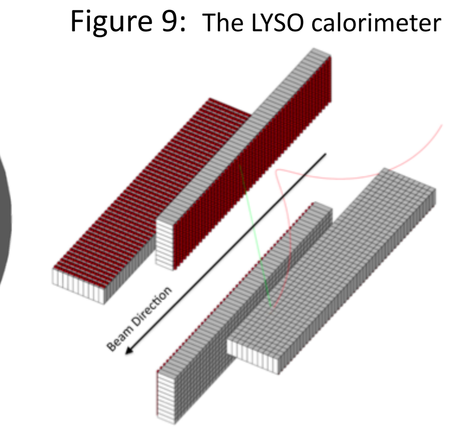


Figure 9: The LYSO calorimeter



The Mu2e design studies predict that, for 3.6×10^{20} protons on target, there will be 0.17±0.07 background events in the signal region. The irreducible background from DIO electrons is predicted to be 0.009±0.006 events. The most important sources of background are from late arriving beam particles: backgrounds from residual anti-protons in the beam (0.06±0.06), radiative π^- capture on the target foils (0.04±0.02), muons decaying in flight (0.034±0.017); the other significant background source is electrons produced as secondaries in cosmic ray showers (0.025±0.025). The backgrounds from late arriving beam particles are suppressed by the beam extinction system.

Summary and Conclusions

- Working schedule: start data taking in 2018.
- Sensitivity for 3.6×10^{20} protons on target:
  - Discover new physics or …
  - … set a limit Rμe < 6×10^{-17} @ 90 % CL
  - 10,000 times better than the previous best experiment
  - Mass scales to O(10,000 TeV) are within reach
- If SUSY is observable at the LHC, many models predict Rμe ≈ 10^{-15}.
  - Mu2e: O(40) events on a background of < 0.3 events.
- The critical path is the solenoid system
- Following the initial run, Fermilab will have a new high intensity proton source, Project-X.
  - If Mu2e sees a signal: study the N(A,Z) dependence
  - If no signal: improve apparatus towards a sensitivity of Rμe < O(10^{-18})
- For more information: http://mu2e.fnal.gov

References:

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2. R. Watanabe et. al., Atomic and Nuclear Data Table, 165 (1993).
3. O. Shanker and R. Roy, Phys. Rev. D55, 7307 (1997).