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# The Mu2e Experiment at Fermilab

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**Abstract**. The Mu2e Collaboration has proposed an experiment at Fermilab to search for the coherent decay of a muon to an electron in the Coulomb field of a nucleus with an expected sensitivity less than $10^{-16}$. In this article the physics motivations and status of the experiment are described.

## 1. Introduction

The recently proposed Mu2e experiment at Fermilab [1] is a search for the Charged Lepton Flavor Violation (CLFV) process $\mu^- N \rightarrow e^- N$, which is the coherent conversion of a muon into an electron in the field of a nucleus. In the process of muon to electron conversion the initial state is a muonic atom and the final state consists of a mono-energetic electron recoiling against an intact atomic nucleus. There are no neutrinos in the final state. The recoiling nucleus is not observed, leaving an observed final state of just the electron, which has the energy of the muon rest mass less corrections for the nuclear recoil and the K-shell binding energy of the muon.

The result of the experiment will be expressed by the ratio:

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

where N(A,Z) denotes a nucleus with mass number A and atomic number Z. The numerator is the rate for the conversion process and the denominator is the rate for muon capture on the same nucleus (N* is the nucleus after the capture).

In the Standard Model, the predicted ratio, $R_{\mu e}$, for the $\mu^- N \rightarrow e^- N$ CLFV process is less than $10^{-50}$ [2]. Though many experimental observations suggest the existence of New Physics (NP) beyond the Standard Model and most new physics scenarios predict that this CLFV process will occur at some level. In many NP models that include a description of neutrino mass, the rates for these processes are enormously enhanced. In particular scenarios predicting that SUSY is within the reach of the LHC also foresee $R_{\mu e} \sim 10^{-15}$, a rate for which Mu2e expects to observe, after 2 years of running, about 40 events on a background of fewer than 0.5 events. An excellent review of CLFV and the flavor physics of leptons can be found in reference [3]. Two classes of diagrams can contribute to conversion. The first class includes magnetic moment loop diagrams with a photon exchanged between the loop and the nucleus; these diagrams can proceed with many different sorts of particles in the loop, including, but not limited to, SUSY particles, heavy neutrinos and a second Higgs Doublet. This class of diagrams also produces non-zero rates for the process $\mu \rightarrow e\gamma$.

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In the second class, the $\mu^- N \rightarrow e^- N$ process is sensitive to NP contributions via contact interactions, such as those expected in Compositeness, Leptoquark, and GUT models with additional gauge bosons and/or anomalous couplings.

**TABLE 1.** Estimated background contributions for the Mu2e experiment. These numbers assume $10^{18}$ stopped muons are delivered in 2 x $10^7$ seconds of run time, an inter-pulse extinction ratio of $10^{-9}$, and a cosmic ray veto efficiency of 99.99%.

| **Category** | **Source** | **Events** |
|---|---|---|
| **Intrinsic** | μ Decay in Orbit<br>Radiative μ Capture | 0.225<br><0.002 |
| **Late Arriving** | Radiative π Capture<br>Beam Electrons<br>μ Decay in Flight<br>π Decay in Flight | 0.072<br>0.036<br><0.063<br><0.001 |
| **Miscellaneous** | Cosmic Ray<br>Long Transit<br>Pat. Recognition Errors | 0.016<br>0.006<br><0.002 |
| **TOTAL** | | **0.42** |

## 2. The experimental technique and background

The Mu2e apparatus is described in detail in the Mu2e proposal [1]. The basic idea behind Mu2e is motivated by the MECO experiment, which in turn derives from the MELC proposal [4].

Using 8 GeV protons from the Fermilab accelerator complex, a beam of low momentum negative muons (<60 MeV/c) is produced via upstream charged pion decays. The beam is stopped on a set of thin Al target foils, where the muons drop to the K-shell, forming a muonic atom. The Bohr radius of the K-shell of muonic Al is about 20 fm and the nuclear radius of Al is about 4 fm, which yields a large overlap between the muon wavefunction and that of the nucleus. The stopped muons have a characteristic decay time, $\tau_\mu^N = 864$ ns.

Genuine $\mu^- N \rightarrow e^- N$ events produce an isolated electron with energy of 104.96 MeV. Energy loss and scattering in the target and detector material result in an observed energy spectrum with a mean of about 104 MeV and an estimated FWHM of 0.9 MeV [5]. About 62% of the signal electrons have energies in the range 103.6-105.0 MeV, which is defined as the signal energy window. Therefore the objective of the Mu2e experiment is to search for an excess in this endpoint energy region.

Muons which slow down and stop in the stopping target can either undergo beta decay in the field of the nucleus (DIO, decay in orbit), be captured (OMC, ordinary muon capture) or convert to electrons. The first is a potential source of background, the second provides the denominator to $R_{\mu e}$ and the third is our signal. Decay in orbit occurs about 40% of the time [6] and the capture about 60% of the time [7].

DIO produces electrons with a continuous energy spectrum: the Michel spectrum of free muon decay is distorted because the outgoing electron can recoil against the atomic nucleus. Near the endpoint the spectrum falls roughly as $(E_{max}-E)^{-5}$ [8] and has a long radiative tail that extends exactly to the muon mass, assuming zero neutrino mass. In one extreme configuration, both neutrinos are at rest and the electron recoils against the intact Al nucleus: this is the configuration where the electron has the maximum energy in the lab frame, 104.96 MeV for muonic Al [9].

The ordinary muon capture, $\mu^- N_Z \rightarrow \nu N_{Z-1}$, is not a source of background electrons, apart a very small contribution from photon produced in radiative capture (RMC), as reported in Table 1.

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So the technique to identify the background from DIO electrons is to carefully measure the energy spectrum from electrons emitted from the target foils. The spectrometer in the Mu2e proposal has a target resolution of <1 MeV at FWHM for 105 MeV electrons. As an example, the fraction of DIO electrons which are expected inside the signal energy window is estimated to be about 2.5 x $10^{-18}$.

## 3. Other background sources

Backgrounds arising from interactions that occur at the production target are overwhelmingly prompt and arrive at the stopping target in time with the muon beam. These backgrounds are eliminated by only accepting electrons appearing 700 ns after the main beam pulse. However, out-of-time protons impinging on the production target will produce background electrons that fall into this delayed signal-timing window. To suppress these Late Arriving Backgrounds (LAB) is necessary to minimize the ratio of out-of-time to in-time protons impinging on the production target. An extinction ratio of $10^{-10}$ was determined to be required [10] to achieve the background levels listed in Table 1.The largest contributions to LAB come from pion capture on the nucleus and from muon decays in flight (i.e, when the electron scatters into the spectrometer acceptance due to interactions in the stopping target material). Electrons, mostly from upstream $\pi°$ decays, can also scatter in the target to produce background. The Late Arriving Backgrounds all scale linearly with the extinction factor and taken together account for about 40% of the total background. The required extinction factor is obtained by means of a pair of AC dipoles, synchronized with the beam so to have the in-time beam passing through a narrow channel in a collimator, designed to absorb all out-of-time protons.

The remaining background sources are dominated by contributions from cosmic rays. Cosmic ray muons can produce background electrons either by decay or by interactions in the material. A combination of passive and active shielding is required to suppress the cosmic ray background to sufficiently small levels. As this background scales linearly with the inefficiency of the veto system, a veto efficiency of 99,99%c is necessary to achieve the cosmic ray background estimate listed in Table 1.

## 4. Beamline

The 8 GeV bunches of protons with a full width of about 100 ns is steered onto a pencil shaped Au (or W) target located in the middle of a solenoid, the Production Solenoid (PS), shown in Figure 1. The PS has a graded magnetic field, with a field of 5 T at the proton-downstream end, falling to about 2.2 T at the proton-upstream end. In the production target, p-Au (W) interactions produce pions that are captured into helical trajectories in the field of the solenoid; these pions decay into muons that are also captured by the field of the solenoid. Mu2e is interested in the backscattered muon beam. The PS graded fiels also forms a magnetic mirror and reflects a portion of the forward going pions and muons, thereby increasing the yield of captured muons.

From the PS the muons enter the S-bend graded field Transport Solenoid (TS), also shown in Figure 1.The bend in the TS induces a dipole term which allows, by appropriate placement of absorbers and collimators, the sign selection of the muon beam and the stopping of any anti-protons accompanying the muon beam. Furthermore the S-shape eliminates a line-of-sight between the PS and the detector to reduce background, rate, and heat load at the detector. The TS has an axial length of 13 meters and a 0.5 meter bore diameter. The field is graded and decreases from 2.5 Tesla near the production target to 2.0 Tesla near the Detector Solenoid (DS).

Inside the DS the muon beam encounters the stopping target. This target is composed of 17 aluminum foils each 200 μm thick with radii that taper from 10.0 to 6.5 cm in the direction of the incoming muon beam. The tapering radii reduce the number of scatters for a signal electron originating in one of the upstream foils. About half the incoming muons will stop in the foils. Downstream of the target there is the Mu2e Detector. Also the DS magnetic field is graded so to form a magnetic mirror that reflects

some backwards going electrons towards the tracker. In the volume occupied by the detector the DS magnetic field is highly uniform at 1.0 T.
The Mu2e experiment will receive an average of about $2x10^{13}$ protons/s in micro-bunches of about 3-6 x $10^7$protons each with a bunch spacing of 1.7 μs. Several schemes are being explored with duty factors in the range of 50-90%. The number of stopped muons per proton on target is estimated to be 0.0025 with a 20% uncertainty, dominated by modeling uncertainties in the $\pi^-$ production at the PS. This modeling is in the process of being tuned to recent data [11].

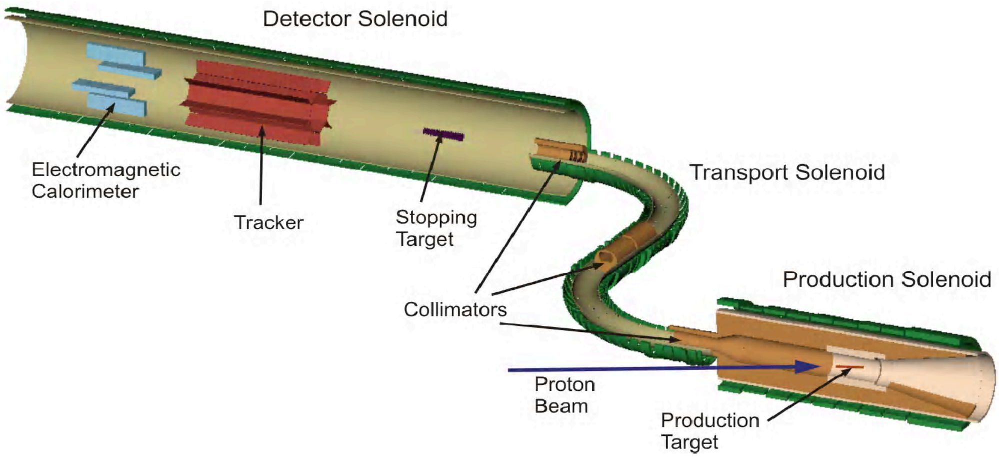


**FIGURE 1.** Diagram of the Mu2e muon beam-line and detector. The proton beam enters from the left. A back-scattered muon beam is captured by the Production Solenoid and transported through the S-bend Transport Solenoid to the stopping targets. Conversion electrons, produced in the stopping target are captured by the magnetic field in the Detector Solenoid and transported through the Tracker, which makes a precision measurement of the momentum. The conversion electrons then strike the Electromagnetic Calorimeter, which produces an event trigger.

## 5. Detector

The Mu2e detector (see Fig.2) has two main components, the tracker and the calorimeter. In the present design the tracker consists of 2.8k 2.4 meter long straw tubes oriented parallel with the muon beamline. The inner radius of the tracker is approximately 38 centimeters. When a conversion or DIO electron is emitted from the stopping target, it travels in a helical trajectory, and, if it has sufficient transverse momentum ($P_T$), its trajectory will be measured by the tracking system. With an inner radius of 38 cm, only electrons with $P_T > 55$ MeV/c will reach the detector and only those with $P_T >$ 90 MeV/c will intersect enough of the tracker to form a reconstructible track. Because almost all tracks from DIO have $P_T < m_\mu /2$ they will never reach the tracker. This is the key to making a measurement of $R_{\mu e}$ with a sensitivity of $0(10^{-17})$, as the apparatus is only sensitive to the tail of the DIO energy distribution. The momentum resolution of the tracker is dominated by scattering (120 keV/c) and by energy loss across the material: the resulting FWHM is estimated to be 900 keV/c for signal electrons. Electrons that pass through the tracker will eventually intersect the electromagnetic calorimeter where they will provide an event trigger plus an energy measurement and a position measurement, both of which can be used to confirm track candidates.
In the present design electromagnetic calorimeter consists of 1.2k Lead Tungstate crystals. They ensure an energy measurement with a resolution of about 5% at 100 MeV and a position resolution of about 1 cm.

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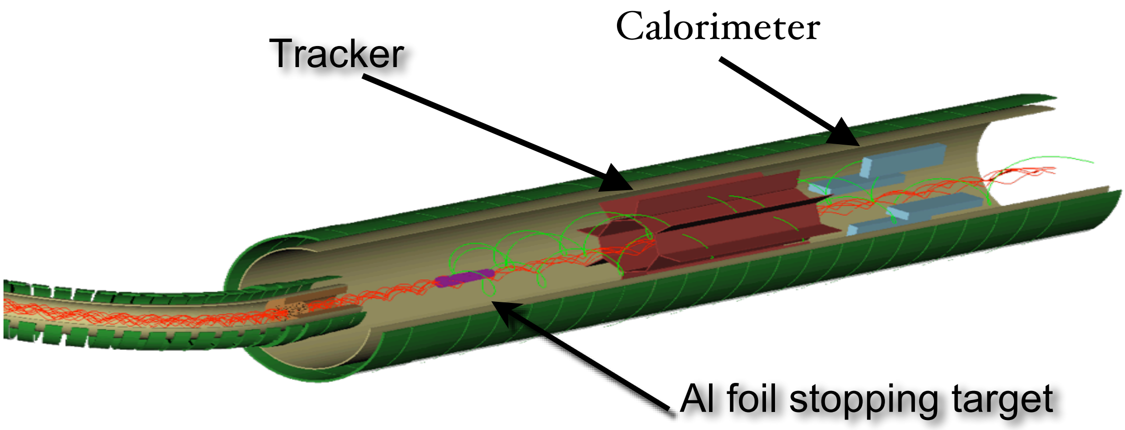


**FIGURE 2**. Layout of the Mu2e detector.

## 6. $R_{\mu e}$ calculation

The Mu2e Experiment will measure the ratio of the muon-to-electron conversion rate to the muon capture rate in Al, i.e:

$$R_{\mu e} = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu_\mu N^*)} = \frac{N_{\mu e}/N_s \cdot 1/\epsilon_{\mu e}}{\Lambda_{\mu\nu}/\Lambda_{\rm tot}\,(=0.609)},$$

where: $N_{\mu e}$ is the number of events in the signal window E > 103.6 MeV: $N_s$ is the total number of muon stops; $\varepsilon_{\mu e}$ is the overall detector acceptance (0.076), which is the product of the calorimeter trigger efficiency (0.80). the fraction of muon captures in the time window (0.51), and the reconstruction and selection efficiency (0.19): $\Lambda_{\mu e}$ is the muon capture rate: and $\Lambda_{tot}$ is the total decay rate (in Al). For a correct evaluation of $R_{\mu e}$ it is evident that some means of confirming the rate and integral number of negative muons which stop on the target foils is crucial. An effective and reliable Muon Stopping Target Monitor will be established by observing the prompt production of muonic x-rays which signal the formation of muonic atoms in the target foils. This objective will be achieved locating a germanium detector where it can view, without serious deadtime. photons coming from the target foils. Such x-rays are unambiguously characteristic of a muonic atom's atomic number Z.

## 7. Status

The Mu2e experiment has received CD-0 approval from the U.S. Department of Energy. At present, a broad R&D program is underway to re-optimize the design of the experiment and to demonstrate the feasibility of the most technically challenging parts of the proposal. The CD-1 approval from the U.S. DOE is expected in Summer of 2011. The critical path for the Mu2e apparatus is the design and construction of the solenoid system. If all resources are made available as required, the solenoids could be installed by 2016.

## 8. Conclusions

The goal of the Mu2e experiment is to observe μ to e conversion or to set an upper limit of < 6 x $10^{-17}$ at the 90% CL and to do so in two years of running. This is 10,000 times better than the previous best limit [12] and mass scales up to 0(10,000 TeV) are within reach. For $R_{\mu e} = 10^{-15}$ the detector would see about 40 events on a background of less than 0.5 events.

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