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

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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 $\sim 10^4$ TeV, far beyond the reach of present or planned high energy colliders. We present the design of the muon beamline and spectrometer, how the experiment fits in the current Fermilab complex, and discuss potential upgrades at Fermilab's Project X.

*Key words:* Tracking detectors, Calorimetry, Muon electron conversion
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## 1. Muon to electron conversion

The Charged Lepton Flavor Violation (CLFV) $\mu \to e$ can occour in the Coulumb field of a nucleus, through the creation of a muonic atom. The final state consists of a mono-energetic electron recoiling against the intact and unobserved atomic nucleus, without any neutrino. The electron in final state has the energy of the muon rest mass less corrections due to the nuclear recoil and the K-shell binding energy of the muon. In the aluminum nucleus case the electron energy is 104.96 MeV, while the lifetime of the bound state is 864 ns. The mu2e experiment aims to measure the ratio

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \text{capture})} \tag{1}$$

where N(A,Z) denotes a nucleus with mass number A and atomic number Z.

In the Standard Model the process is possible only through the intermediate mixing of massive neutrinos and the expected rate is $\approx 10^{-52}$. Other processes of physics beyond Standard Model can also mediate the conversion (see fig.1). In particular, SUSY predicts $R_{\mu e}$ of order of $10^{-15}$ for masses and coupling accessible at LHC[1]. Mu2e is designed to reach a sensitivity of $10^{-17}$, so we could expect in this particular model O(40) signal events in case of $R_{\mu e} \approx 10^{-15}$, otherwise we will set a limit for $R_{\mu e} < 6 \times 10^{-17}$ @ 90% $CL$.

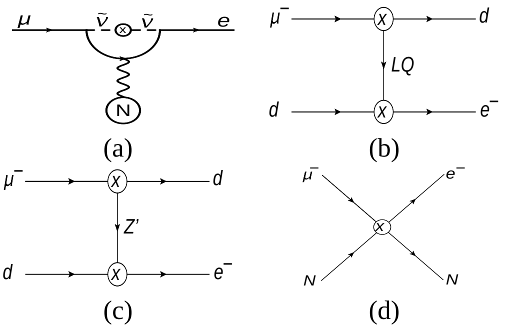


Figure 1: Physics processes beyond Standard Model which can mediate the $\mu \to e$ conversion: a) SUSY magnetic moment diagram, b) Lepto-quark exchange, c) Z' exchange, d) Effective contact interaction

## 2. Beam and solenoids

The Mu2e experimental setup is composed of three solenoids as shown in fig.2. In the first one, the Production Solenoid (PS), an 8 GeV proton beam strikes every 1694 ns a tungsten production target (PT) to produce pions decaying into muons. A graded magnetic field, from 5 T to 2.5 T collects negative particles toward the entrance of the transport solenoid (TS) which has an S-bend shape in order to get rid of neutral particles. The graded magnetic field, from 2.5 T to 2 T, and a system of collimators apply charge and momentum selection on the muon beam and deliver the particles to the entrance of the third system, the Detector Solenoid (DS). The stopping target (ST) in the DS is a set of aluminum foils designed to stop the muons with with a probabilty of 0.5 per muon entering in the DS. The electrons coming out from the ST describe an helix through the spectrometer (see section 3). The graded magnetic field (2 T to 1 T) in the ST region reflects some electrons headed upstream of the muon beam. Fewer than $10^{-10}$ protons are required to arrive between the beam pulses to avoid backgrounds from beam flash during the whole period between two bunches, so a beam extinction system will be used to meet the requirement and a system to measure the achieved extinction is being designed.

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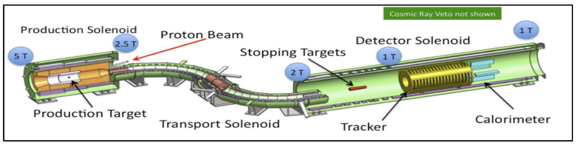


Figure 2: Solenoid system: the beam direction is from left to right.

## 3. Tracker and Calorimeter

The spectrometer in the DS is composed by a tracker and calorimeter:

The **tracker** is composed of 5 mm diameter straw tubes wrapped with mylar insulators, organized in two layers of 50 increasing-length straws to form a trapezoidal structure called panel. Six panels are placed in two levels of three panels each to form a plane. The two levels are rotated each other by 30 degrees, and the plane has an inner unstrumented region, to avoid hits from low-momentum particles (fig.3). Two planes placed back to back, and rotated by 30 degrees each other, form a station. The whole tracker is made by 18 parallel stations (fig.3). The expected resolution of the tracking system is ≤ 150 Kev/c.

The **calorimeter** is composed of 4 rectangular vanes, placed as in fig.3. Each vane is a matrix of LYSO crystals, 11 radially and 44 along the beam axis. The dimension of the crystal is $3{\times}3{\times}11cm^3$ and an APD based readout is placed on the squared face of the crystal. The APD's are placed so that the conversion electrons enter the opposite face. The expected resolution for the calorimeter is ≤ 2%@100 MeV.

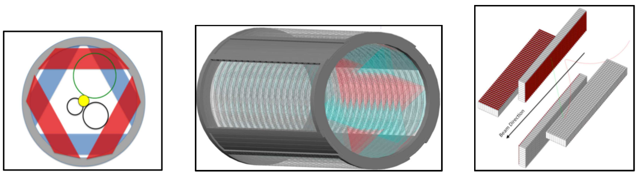

Figure 3: The tracking and calorimeter system. From left to right: frontal view of a plane, lateral view of the tracker, calorimeter positioning w.r.t. beam axis.

## 4. The backgrounds

The main sources of background are the following:

- Decay In Orbit (DIO): About 40% of captured muons decay in an electron plus two neutrinos:

$$\mu^- \to e^- \nu_\mu \overline{\nu}_e \tag{2}$$

  The electron spectrum is shown in fig.4[2]. Low momentum DIO electrons pass through the inner empty regions of tracker and calorimeter without registering hits. We search for signal electrons in the momentum region [103.5 MeV/c .. 104.7 MeV/c], so the high momentum tail of the DIO distribution represents the irreducible physics background to $\mu \to e$ conversion. This background is suppressed by means of the designed high resolution of the tracker.

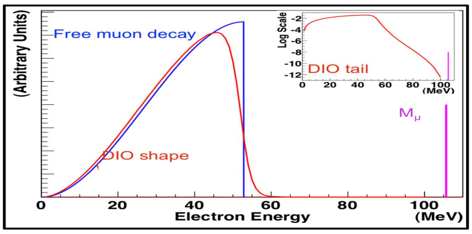


Figure 4: DIO momentum spectrum. The purple spike is the signal $\mu \to e$ electron momentum, and the right top plot is a zoomed view of the DIO spectrum tail.

- Muon nuclear capture: About 60% of the stopped muons are captured by the aluminum nucleus resulting in a nuclear breakup and emission of protons, photons and neutrons. They are discriminated due to their neutral charge (photons and neutrons) and different energy deposition in the straw gas w.r.t. signal electrons (protons).

- Prompt beam flash: It is made by particles produced in the production target, whose passing in the DS happens almost entirely in the first 600 ns after the beam pulse. A "live" window for the signal search starts at about 700 ns after the spill, in order to avoid contamination from the prompt beam related background.

- Radiative Pion Capture: Pions that arrive at the aluminum foils without decaying can be stopped and produce photons and electrons by:

$$\pi^- N \to \gamma N^{Z-1}, \gamma \to e^+ e^- \tag{3}$$

- Other sources: Irriducible background comes from cosmic rays, decay-in-flight pions, decay-in-flight muons and anti-protons coming from the beam.

The table below shows a list of the expected background event normalized to $3.6{\times}10^{20}$ protons on target that we expect to have in three year running, starting from 2019.

| Bkg events for $3.6 \times 10^{20}$ p on target | |
|---|---|
| DIO electrons | $0.22 \pm 0.06$ |
| Cosmic rays | $0.050 \pm 0.025$ |
| Decay-in-flight $\pi$ | $0.0030 \pm 0.0015$ |
| Anti-protons from beam | $0.100 \pm 0.035$ |
| Radiative $\pi$ capture | $0.030 \pm 0.007$ |
| Decay-in-flight $\mu$ | $0.010 \pm 0.003$ |
| Beam electrons | $0.0006 \pm 0.0003$ |
| Total | $0.41 \pm 0.08$ |

In the future the Fermilab's Project X will increase the muon statistics: we will vary Z of the foils to study new physics in case of signal, otherwise we will 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