Searching for Muon to electron conversion: The Mu2e experiment at Fermilab

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Mu2e: the basics

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

$$\mu^- N \rightarrow e^- N$$

- This would violate **charged lepton flavor**, something that has never been seen before
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is $< 10^{-50}$)

- Mu2e goal is a 10^4 improvement! (previous limit 7×10^{-13} from SINDRUM II)

The Mu2e experiment at Fermilab

Measure the ratio of conversions to muon captures:

$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}$$

- Signal of CLFV conversion is single monoenergetic electron
- Backgrounds:
 - Beam related: $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$
 - Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
 - Muon Decay in orbit: $\mu^- N \rightarrow e^- N \nu_\mu \bar{\nu}_e$

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Mu2e Proton Beam

- 8 GeV 8 kW proton beam using protons from booster
- Resonantly extracted to get pulses of 4×10^7 protons separated by $1.7 \mu\text{s}$
- Runs simultaneously with NOVA
- Extinction factor (ratio of out-of-time protons to in-time protons) of $> 10^{-10}$

Mu2e experimental setup

- Consists of three superconducting solenoids:
 - Production Solenoid (PS)
 - Transport Solenoid (TS)
 - Detector Solenoid (DS)

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Production Target and Solenoid produce slow muon beam in the reverse direction of the proton beam

- Tungsten production target
- Magnetic mirror traps and redirects back to TS

Transport Solenoid sign selects charged particles

Detector solenoid directs electrons to detector elements

- Muons stopped on thin aluminum foils, again graded field for magnetic mirror
- Constant field in tracking volume
- High precision straw tracker in vacuum
- Electromagnetic calorimeter for PID

Straw Tracker Detector

- 18 stations, each containing $12 \times 120^\circ$ panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than $200 \text{ keV}/c$

Straw Tracker Detector

- $\sim 21,000$ low mass straw tubes in vacuum
- 5 mm diameter, $15\text{ }\mu\text{m}$ thick mylar walls
- Measure transverse position to $\sim 200\text{ }\mu\text{m}$, longitudinal position along straw to $\sim 4\text{ cm}$
- Waveform digitized to reject proton hits

8 straw tracker prototype used to tune simulation and verify expected resolution

Transverse Resolution

Longitudinal Resolution

Efficiency

Calorimeter

- Two annular disks separated by half a “wavelength” (70cm) of electron’s helical path
 - Maximize probability to hit at least one disk
- Each disk contains 674 undoped CsI $34 \times 34 \times 200 \text{ mm}^3$ crystals read out by SiPMs
- 0.5 ns time, 5% energy, 1 cm position measurement independent of straw tracker
- Provides particle ID for track rejection
- Seed for tracking algorithm / trigger

Calorimeter Prototypes

- Small 3x3 prototype tested in 80-120 MeV e^- beam
 - $\sigma_E \sim 6.5\%$ and $\sigma_t \sim 110\text{ps}$ at 100 MeV
- Larger preproduction prototype (51 crystals, 102 SiPMs, 102 FEE boards)

Cosmic ray veto

- Expect cosmic rays to produce 1 conversion-like event per day
- 4 overlapping layers of scintillator, read out on both ends with SiPMs
 - Veto on 3-fold coincidence
- Covers entire DS, half of TS, better than 10^{-4} inefficiency

Expected backgrounds for 3 year run

Process	Expected event yield
Cosmic ray muons	$0.21 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
DIO	$0.14 \pm 0.03(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

- Fewer than ~ 0.5 background events expected over entire run
- 3.6×10^{20} protons on target over 3 years $\rightarrow \sim 10^{18}$ stopped muons

Simulation and Reconstruction

1 μ s selection window after beam flash

Hits selected by track finder within ± 50 ns selection window around potential track

- Detailed Geant4 simulation of full detector
- Straw response tuned to data and detector prototype measurements
- Simulate from production target forward (including backgrounds)
- Kalman Filter track fit

Sensitivity

- Discovery reach (5σ): $R_{\mu e} \geq 2 \times 10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8 \times 10^{-17}$

Construction

Schedule