μ2E – A search for Muon to Electron Direct Conversion

$\mu^- N \rightarrow e^- N$, at Fermilab

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The μ2e Goal

The Goal

The goal of the μ2E experiment is to measure the coherent (neutrinoless) conversion of a negative muon into an electron in the presence of a nuclear field.

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

The experiment will measure the branching fraction for the coherent process relative to ordinary muon capture.

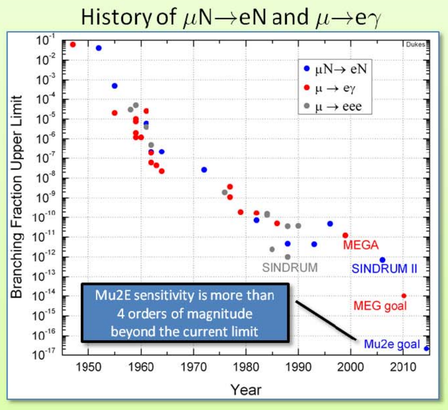
$$B(\mu N \rightarrow eN) = \frac{\Gamma(\mu^- N_Z \rightarrow e^- N_Z}{\Gamma(\mu^- N^Z \rightarrow \nu N^{Z-1})}$$

The goal is to achieve a single event sensitivity in the first operational phase of 2×10^{-17}, where the expected physics background in the signal region would be only 0.2 events[i]. This level of expected sensitivity would yield a new bound almost 4 orders of magnitude beyond the current limit.

$$B(\mu N \rightarrow eN) < 6\times10^{-17}\ (90\%CL)$$

With this level of sensitivity, a single observed conversion event would be compelling evidence for physics beyond the standard model.

History of μN→eN and $\mu\rightarrow e\gamma$



[i] Another 0.2 events are expected from out of time beam sources

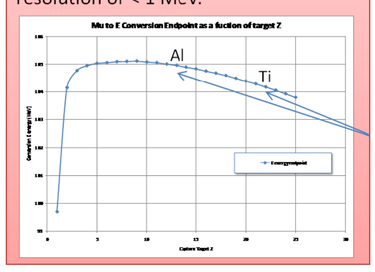
The Signal and Background

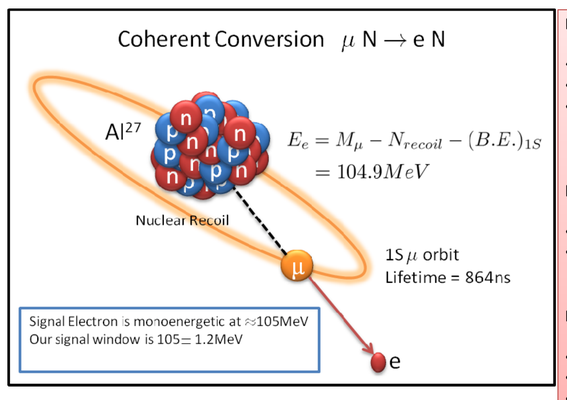
Coherent Conversion $\mu \rightarrow$ e Signal

The coherent conversion of the muon into an electron is characterized by the ejection of a mono energetic electron, whose energy is the muon rest mass minus the binding energy and nuclear recoil of the 1S muonic atom.

$$E_e = M_\mu - N_{recoil} - (B.E.)^{1S}_\mu$$

In the case of an Al^{27} stopping target the 1S binding energy is ≈ 475eV. This results in the conversion electron an energy being 104.96MeV.
We look for signal events centered around this value within an energy resolution of < 1 MeV.

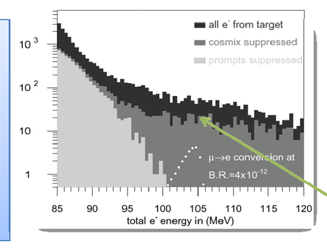




For low Z nuclei the binding energy of the 1S muonic atom can be approximated as:

$$(B.E.)^{1S}_\mu \approx 13.6\frac{m_\mu}{m_e}Z^2 ev$$

This makes Aluminum (Al^{27}) and Titanium (Ti^{47}) the preferred target choices due to endpoint energy, nuclear capture rates and requirement that $M_{Z-1} > M_Z$ to suppress radiative μ capture background.

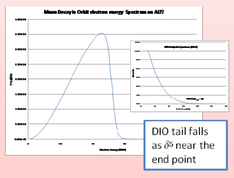


Physics Backgrounds

Muon decay in orbit (DIO)

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

- Shares same endpoint as $\mu \rightarrow$ e
- But the rate drops as $\delta^5 = (E_{max} - E_e)^5$
- Mandates tracker resolution < 200 keV to reduce contamination of the signal region.



Radiative Pion Capture

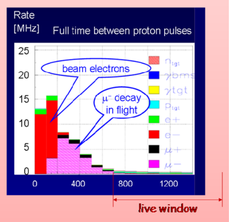
$$\pi^- N \rightarrow \gamma N^{Z-1}, \quad \gamma \rightarrow e^+e^-$$

- 1.2% of decay electrons have E > 105MeV
- Places a limit on the π contamination in the beam during detection window.

Radiative Muon Capture

$$\mu^- N \rightarrow \gamma\nu_\mu N^{Z-1}, \quad \gamma \rightarrow e^+e^-$$

- Max E_γ = 102.5MeV
- $P(e^- > 100.5\ MeV) \approx 2.5\times10^{-5}$
- Restricts stopping target: $M_{Z-1} > M_Z$



Beam realated background is suppressed by a delayed "live" window which starts 770ns after the beam pulse

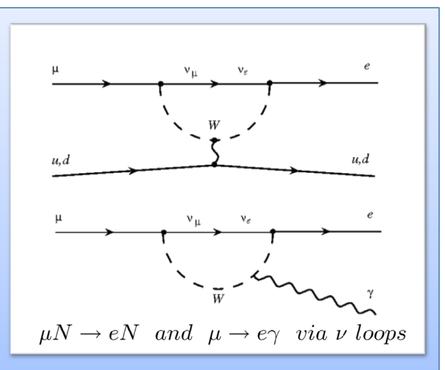
Background contributions from ALL sources are expected at 0.4 events in the signal region for an integrated sensitivity of 2×10^{-17}

μ2e In the Standard Model

- There is no natural Charge Lepton Flavor Violation (CLFV) in the standard model
- BUT lepton flavor violation CAN occur through the intermediate mixing of massive neutrinos.
- The rate for $\mu\rightarrow e\gamma$ via a neutrino loop depends on the ν mass splitting and couplings

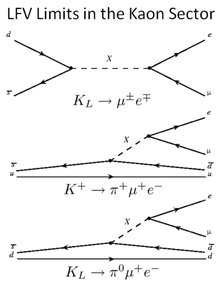
$$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2$$

- For our current knowledge of the neutrino parameters we expect neutrino induced lepton flavor violation in $Br(\mu\rightarrow e\gamma) \approx 10^{-52}$



This is so tiny, that ANY observed $\mu \rightarrow$ e signal is a sign for new physics

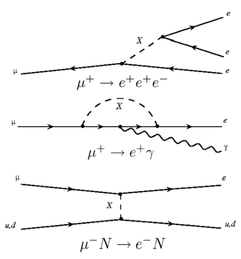
LFV Limits in the Kaon Sector



Current LFV Limits come from both Kaon and Muon results

Current Reach of Lepton Favor Violation Experiments		
Process	Limit	Mass Limit
$K_L \rightarrow \mu^\pm e^\mp$	4.7×10^{-12}	150 TeV/c^2
$K^+ \rightarrow \pi^+\mu^+e^-$	4×10^{-11}	31 TeV/c^2
$K_L \rightarrow \pi^0\mu^+e^-$	3.210^{-10}	37 TeV/c^2
$\mu^+ \rightarrow e^+e^+e^-$	1×10^{-12}	86 TeV/c^2
$\mu^+ \rightarrow e^+\gamma$	1.2×10^{-11}	21 TeV/c^2
$\mu^- N \rightarrow e^- N$	6.1×10^{-13}	365 TeV/c^2

LFV Limits in the Muon Sector



μ2e Beyond the Standard Model

New Physics

The strength of the muon conversion channels is that ANY signal is immediately a sign of physics beyond the standard model.

In particular the effects of Super Symmetry are manifest in the μ N → e N channel at a branching ratio of 10^{15}, two orders of magnitude ABOVE the expected sensitivity of μ2E.

The effective reach of high precision LFV physics is evident when the effective mass scales for new physics are calculated. If we assume a $\mu\rightarrow$ e conversion rate of of 10^{-16}, then we see that μ2E will be able to probe processes mediated up the scale of thousands of TeV!

This poises μ2E as best window into observing new physics at the terascale.

Current Limits on Lepton Favor Violation		
Process	Limit	SUSY Prediction
$\mu^- N \rightarrow e^- N$	10^{-12}	10^{-15}
$\mu^+ \rightarrow e^+\gamma$	10^{-11}	10^{-13}
$\tau \rightarrow \mu\gamma$	10^{-6}	10^{-9}

The μ2E channel is not limited by backgrounds like it's sister channel $\mu \rightarrow e\gamma$ or $\tau \rightarrow \mu\gamma$.

This means the SUSY prediction is two orders of magnitude above the expected phase 1 experimental sensitivity of 10^{-17}

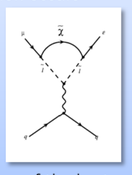
Susy Sensitivity

In super symmetric models, μ to e conversion occurs naturally through a simple SUSY penguin.

This diagram gives an expected branching ratio:

$$B(\mu N \rightarrow eN)_{SUSY} \simeq O(10^{-15})$$

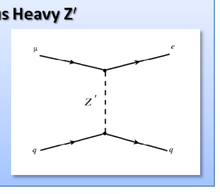
Which is well above the expected signal Event sensitivity of 10^{-17}, meaning μ2e is one of the best probes for SUSY.



Anomalous Heavy Z'

The reach of μ 2 e at 10^{-17} corresponds to probing for an anomalous heavy $Z' \rightarrow \mu e$ coupling. Where the Z mass can be as high as:

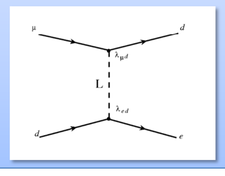
$$M_{Z'} = 3000\ TeV/c^2$$



LeptoQuarks

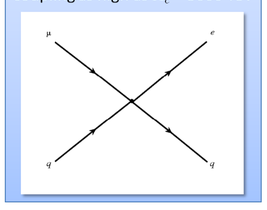
LeptoQuark models provide a tree level path for μ to e conversion. For the expected single event sensitivities, $\mu N \rightarrow$ eN probes to an effective propagator mass:

$$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}\ TeV/c^2$$



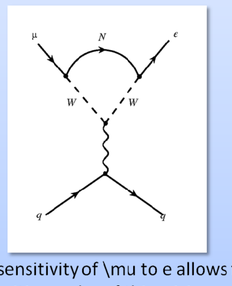
Compositness (4-Fermion)

With a four fermion point like interaction characterized by a coupling Λ_c the $\mu\rightarrow$e conversion process at a branching fraction BR = 10^{-16} gives access to a coupling as high as Λ_c = 3000 TeV



Heavy Neutrinos

Another probe that the μ to e process gives is for the presence of a new heavy neutrino mass state N (i.e. not m_1 m_2 or m_3) which can contribute to the mixing diagram



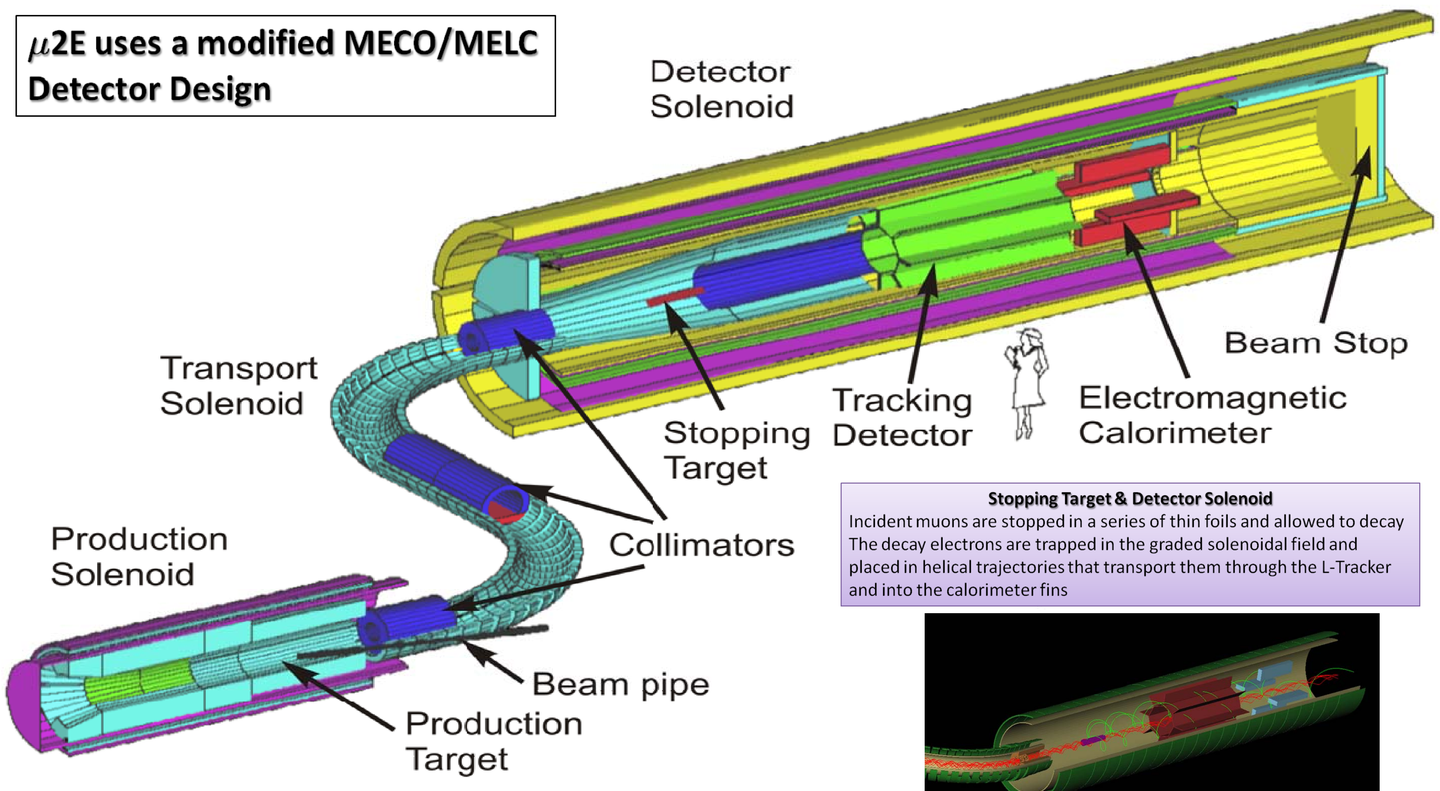
The sensitivity of \mu to e allows for a sensitive probe of this mixing where the matrix element of coupling of the new mass state to the charged leptons is:

$$\left|U^\star_{\mu N}U_{eN}\right| \approx 8\times10^{-13}$$

The reach of μ2E is thousands of TeV!

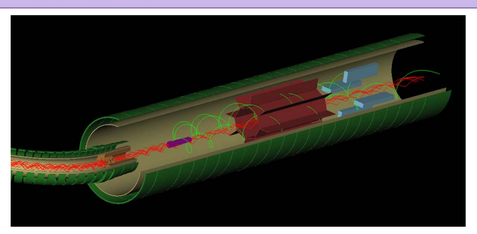
The μ2e Detector Design

μ2E uses a modified MECO/MELC Detector Design



Stopping Target & Detector Solenoid

Incident muons are stopped in a series of thin foils and allowed to decay The decay electrons are trapped in the graded solenoidal field and placed in helical trajectories that transport them through the L-Tracker and into the calorimeter fins



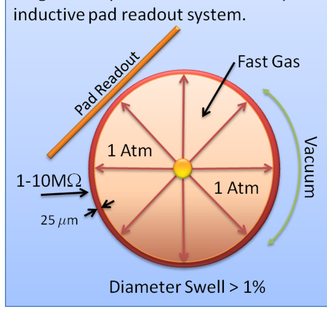
The Longitudinal Tracker

The L-Tracker

The Longitudinal tracker is designed to reconstruct the helical trajectory of the conversion electrons, and reconstruct the track momentum to a resolution of better than 200keV.

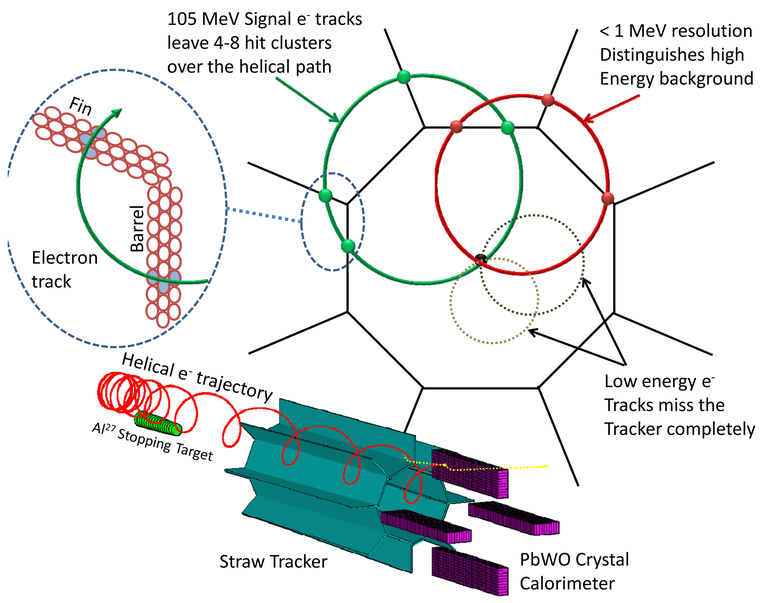
Mu2E Resistive Straws

The L-tracker will use 2.9m long resistive cathode straw tubes in vacuum. Each straw is designed to handle an occupancy of ≈1MHz with longitudinal position determined by an inductive pad readout system.



Straw Properties	
Material	PEEK or Carbon loaded Kapton
Resistivity	1-10 MΩ
Wall thickness	25 μm
Cond. coating (opt)	1 μm (Cu)
Operating Presure	1 Atm
Swell Limit	1%
Radiation Dose	>100-200(Gy)

PEEK (PolyEther-Ether-Ketone) Tube Prototypes

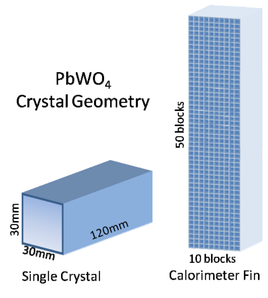
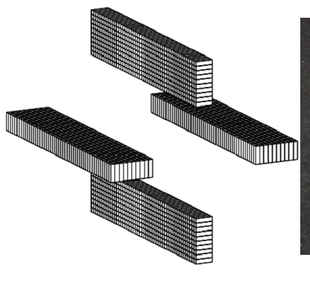
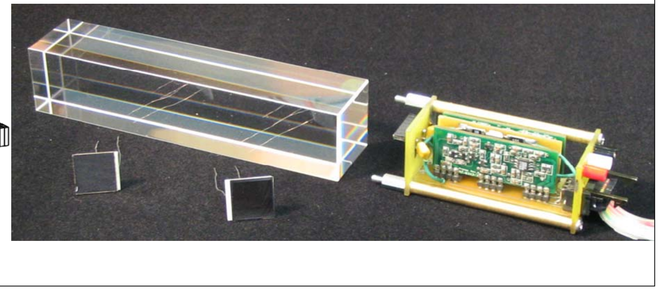


The Triggering Calorimeter

A Calorimeter Trigger

The electromagnetic calorimeter, is the primary trigger device for the μ2E experiment. The 4-Fin design suppresses the low energy particle flux through its geometric acceptance, in the same manner as the L-tracker.

To suppress the flux of low energy (E_e < 55MeV) D.I.O. events that trigger the calorimeter, a two stage trigger is implimented. The L0 trigger accepts only super clusters in the calorimeter over a 40MeV threshold. The L1 trigger algorithm identifies and more precisely sums the shower energy, placing the L1 trigger threshold at 65MeV. This two stage calorimeter trigger should result in an over all trigger rate of 1-2kHz, while maintaining a >90% trigger efficiency for high energy electrons.



Calorimeter Properties	
Resolution	5%
Material	$PbWO_4$
Readout	Dual APD
Blocks	500 per fin, 4 fins
Segmentation	$30\times30\times120mm^3$
Trigger Rate	1kHz
Light yield	20-30p.e./MeV