The last oscillation: mu2e at Fermilab

Vadim Rusu
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Flavor oscillations

- Maybe the most important feature of the SM
  - why are 3 families anyway?
- Quarks change flavor (CKM), neutral leptons change flavor (MNS)
- Do charged leptons oscillate? (CLFV)
  - answer:
Maybe the most important feature of the SM
  - why are 3 families anyway?

Quarks change flavor (CKM), neutral leptons change flavor (MNS)

Do charged leptons oscillate? (CLFV)
  - answer: **YES**
Neutrinos have mass

$\nu_{\mu} \rightarrow \nu_{\tau}$

$\mu \rightarrow e + \gamma$
Neutrinos have mass

\[
\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}
\]
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- not going to measure this one soon
- CLFV: not a new idea
- In fact, almost everyone looked for this
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\( \mu \) discovered in 1936
○ CLFV: not a new idea

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Feinberg 1958 loop calculation
\[ \mu \rightarrow e\gamma \sim 10^{-4} - 10^{-5} \]
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Non observation of $\mu \rightarrow e\gamma$ (implies two neutrinos)
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Best limit so far

10^{-1} \quad 10^{-3} \quad 10^{-5} \quad 10^{-7} \quad 10^{-9} \quad 10^{-11} \quad 10^{-13} \quad 10^{-15} \quad 10^{-17} \quad 10^{-19}

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\[ \text{mu2e intends to improve by 10000 and then 100 more w/ Project X} \]
Supersymmetry

rate $\sim 10^{-15}$

Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8 \times 10^{-13}$

Compositeness

$\Lambda_c \sim 3000$ TeV

Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4}g(H_{\mu\mu})$

Leptoquark

$M_{LQ} = 3000 (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c$^2$

Heavy Z'

Anom. Z Coupling

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

also see Flavour physics of leptons and dipole moments, arXiv:0801.1826
Model independent

\[ L = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu}^\nu + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma_\mu q_L \]

\[ \kappa \ll 1 \]

magnetic moment type operator

\[ \mu \rightarrow e\gamma \text{ rate } \sim 300X \]

\[ \mu N \rightarrow eN \text{ rate} \]

\[ \kappa \gg 1 \]

four-fermion interaction

\[ \mu N \rightarrow eN \text{ rate many orders of magnitude greater than } \mu \rightarrow e\gamma \text{ rate} \]
Muon to electron conversion

μ → e + γ

Time scale for entire process ~μs
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- the Bohr radius is 20fm → muon sees nucleus (∼4fm)
- conversion electron ∼105MeV
  - correct for recoil and BE

Time scale for entire process ∼μs

X Rays

~105MeV
But what really happens...

- Muon decay in orbit
- Nuclear muon capture
Muon decay

\[ E_e(\text{max}) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV} \]

\( \mu \) decay in orbit spectrum \( ^{27}\text{Al} \)

Michel spectrum from free decay
Muon decay

\[ \mu \text{ decay in orbit spectrum } ^{27}\text{Al} \]
Nuclear muon capture

- $\mu+A(Z,N) \rightarrow \nu_\mu+A(Z',N')+an+bp+c\gamma$
  - For Al: $a \approx 1.5$, $b \approx 0.1$, $c \approx 2$

- **Protons** are easy to reconstruct but
  - 20-30x more ionizing $\rightarrow$ high charge
  - Spurious hits

- **Neutrons** are not a direct tracking problem but
  - High fluences affect detectors
  - Can knock out electrons, photons

- $\gamma$'s can convert into $e^+e^-$

Rates in the tracker are dominated by neutron induced processes

Highest rate in the live window $< 300$kHz
Muon decay in orbit

Nuclear muon capture

and others:

- radiative pion captures
- beam electrons, antiprotons
- in flight $\mu$ and $\pi$ decays
- cosmic rays

...and other processes

more on all those later!
SINDRUM II at PSI

- Final Run on Au at PSI
  - $R_{\mu e} < 7 \times 10^{-13}$
- 1 event past the end of the spectrum
- Radiative pions, CR?
- PSI has a DC beam - more on this later

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

A textbook mu2e experiment
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- 50000000000/s
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BNL Seminar
Vadim Rusu - The last oscillation: mu2e
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○ Perfect resolution
  ◆ spectrometer in vacuum with zero mass
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  - spectrometer in vacuum with zero mass

Too hard!!!!!!
maybe is time to look at etomu?
mu2e collaboration

Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
University of Massachusetts, Amherst
Lawrence Berkeley National Laboratory
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington, Seattle

Istituto G. Marconi Roma
Laboratori Nazionale di Frascati
Università di Pisa, Pisa
INFN Lecce and Università del Salento
Gruppo Collegato di Udine

Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia

~130 collaborators
Booster: $4 \times 10^{12}$ p/batch every 1/15s
- Nova: 12 stacked in the Recycler and then to MI
- MI cycle 1.33s
- 8 batches available

2 used by mu2e
- Recycler RF manipulation into 4 bunches ~200ns each
- Transfer to Debuncher

Debuncher period $1.7\mu$s
- Resonant extraction from Debuncher $\rightarrow$ beam to muon production target

6×$10^{12}$ p/s delivered to muon production
- 3.1×$10^7$ protons/bunch
Reuse as much as possible the current collider complex

- Small changes to the existing antiproton rings
- Allow mu2e and g-2 this decade (8GeV muon program)
- No interference with the 120GeV neutrino program (Nova)
- $\pi$ from $p$ in PS - $\pi \rightarrow \mu \nu$
- $\mu$’s spiral down in S shape solenoid (TS)
- $\mu$’s end on the conversion target in DS

Production Solenoid

Transport Solenoid

Detector Solenoid

$10^{-4}$ Torr vacuum throughout
Protons leave through thin window (extinction measurement after)

Proton Target (W rod 160 × 3 mm)

Pions (captured in gradient B)

Protons enter here (opposite to outgoing µ’s)

→ 4m × 0.3m ←
Curved solenoid eliminates line of sight
- No neutrals transport

Sign selection
- S shape solenoid + collimator

2.0T

13.1m x 0.25m

2.5T
Detection

- **Calorimeter**
  - ~1024 3.5 x 3.5 x 12 cm PbWO4 or LYSO
  - 2% resolution

- **Tracker**
  - Transverse geometry
  - 21600 straws
  - 18 stations

Magnetic mirror increases acceptance

Beam dump

Tracker hits → Radius → p (=qBR)

Calorimeter charge → Energy

Shielding and cosmic veto

10 m × 0.95 m

Al foils

p absorber
**mu2e calorimeter**

- **Vane (baseline)**
  - electron tracks spiral into flat faces
  - neutrons from stopping target hit edge

- **Disk (new idea)**
  - facing neutrons, so potentially more accidental activity worsening resolution
  - charge-symmetric!
- Trigger the detector
- Confirm the track
- Separate measurement
Tracker

- 21600 straws in vacuum
  - ~39 hits/track
  - <0.25 X0 for a typical track
- Electronics at straw end
- All support at large radius

- Self supporting panels assembled into planes
- Planes assembled into stations
- Rotating 60° for improved stereo
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Tracking at high radius only ensures operability (beam flash!)
**mu2e straw**

- **15 microns Mylar**
  - 2x6.25μm Mylar spiral wound
  - 500Å Al
  - 200Å Au on inner surface

- **5mm diameter straws**
  - 25 μm W sense wire (Au covered)
  - 334-1174 mm in length
  - ArCO₂ (80/20) at HV<1500
- Single proton pulse
  - particle hits in 500-1695ns window

Problem: find the red track
- Pattern recognition very hard

Good timing helps (±50 ns around C.E.)
Measuring the 3’rd coordinate

- z along the straw
  - obtained at high precision after the fit (stereo)
  - Crucial for pattern recognition
- Time division (read both ends of the straw)
Achieved 3.5cm with mu2e straws

- Limited by noise → could improve (performance already to spec)
Tracker performance

- Studied with full G4 simulations
- Realistic background rates included

- Crystal ball function for intrinsic tracker resolution
  - Core $\sigma=115\text{keV/c}$
  - Tail $\sigma=176\text{keV/c}$
- Signal simulation
  - FWHM$\approx1\text{MeV/c}$
  - $\approx2/3$ resolution = straggling before tracker
    - Al foils
    - Proton absorber
~100k events with P>80MeV
- well understood calculations (very important)
- \( N_{\text{bkg}} = \text{Theory} \oplus \text{Resolution} \)
  - add effect of changing reso here
- Special runs varying target foils, field, location of targets
- Monoenergetic line from \( \pi^+ \rightarrow e^+ \nu \)
  - \( \sim 70\text{MeV} \) \( e^+ \)
- New ideas being looked at
  - electrons from cosmic muons
Cosmic muons
(why a cosmic veto)

- The easiest way to make a 105MeV electron
- Hermetic around the detector
- 99.99% efficient
- <5ns time resolution
- Resist neutron flux

In some regions neutron flux too high
Solution: cathode strip chambers → neutron blind
Radiative Pion Captures

- $\pi N \rightarrow \gamma N'$
- $\gamma N \rightarrow e^- e^+ N$

Fortunately, $\tau_{\pi} \ll \tau_{\mu}$

- waiting helps

$e^+ \approx e^-$

- measure $e^+$ (use $P$ sidebands for extrapolation)

$\gamma$ momentum can extend to $m_\pi$ peak at $\sim 110\text{MeV}$
- Beam electrons, $\mu$ and $\pi$ decays in flight
  - potential backgrounds

- Extinction between pulses < $10^{-10}$
  - $e = N_p\text{ out-of-pulse} / N_p\text{ in-pulse}$
  - requirement based on simulations

- AC dipole + collimators

- We also need to measure this
  - Fast response measurement upstream
  - Integrate (~1 hours) for a statistical significant number of secondary tracks
3 years of $1.2 \times 10^{20}$ p/year (8kW beam power)

For $R_{\mu e} = 10^{-15} \sim 40$ events
A look (far) ahead

- Intense proton source that provides beam to
  - MI (neutrino program)
  - 8 GeV physics program
- Rich muon physics
  - mu2e
  - $\mu \rightarrow e \gamma$
  - muonium-antimuonium oscillations
  - Others

**mu2e signal?**

- YES
- NO

- Change target
- Repeat - higher sensitivity

- Prompt backgrounds redesign muon beamline and detector
- Higher rates, need to reduce backgrounds redesign muon beamline, detector, cosmic veto
Solenoids drive the schedule

Start detector construction in 2 years

Expect to start cosmics run in 2019-2020
Conclusions

- mu2e is a discovery experiment
  - 10000× more sensitive than last
- In the light of first LHC data it is even more important now to look for effects of new physics from scales >>LHC
- mu2e is capitalizing on a large existing infrastructure at Fermilab
- A very challenging experiment (where would be the fun if not) with very advanced understanding of the problems and how to address them

http://mu2e.fnal.gov