The Mu2e Experiment

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Heavy Quarks and Leptons 2018
Yamagata, Japan
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The Mu2e Collaboration

Over 200 scientists
from 37 institutions

Argonne National Laboratory • Boston University •
Brookhaven National Laboratory • Lawrence Berkeley
National Laboratory and University of California, Berkeley •
University of California, Davis • University of California, Irvine
• California Institute of Technology • City University of New
York • Joint Institute for Nuclear Research, Dubna • Duke
University • Fermi National Accelerator Laboratory •
Laboratori Nazionali di Frascati • INFN Genova • Helmholtz-
Zentrum Dresden-Rossendorf • University of Houston •
Institute for High Energy Physics, Protvino • Kansas State
University • INFN Lecce and Università del Salento • Lewis
University • University of Liverpool • University College
London • University of Louisville • University of Manchester •
Laboratori Nazionali di Frascati and Università Marconi Roma
• University of Minnesota • Institute for Nuclear Research,
Moscow • Muons Inc. • Northern Illinois University •
Northwestern University • Novosibirsk State University/
Budker Institute of Nuclear Physics • INFN Pisa • Purdue
University • University of South Alabama • Sun Yat Sen
University • University of Virginia • University of Washington
• Yale University

The Mu2e Collaboration, Feb 2017
Overlooking the detector hall.

Muons are cool

- Muography
- μ SR
- Muon-catalyzed fusion?
- Eventual muon collider experiments?

They can only decay into an electron.

- With ν_μ and $\bar{\nu}_e$.
- Maybe radiative decay with a photon.
- e^- momentum distribution elucidated the V-A structure of weak interactions.

Charged lepton flavour violation? (CLFV)

- τ branching ratios are much higher, but we can make and handle μ much more easily.

Lepton Flavour

- An accidental symmetry: not required to be conserved, and neutrino oscillation is effectively evidence for violation.
- So can we observe it in the heavy leptons?
- This happens, but the Standard Model (w/massive neutrinos) branching ratio is $\propto \frac{\Delta m_\nu^4}{m_W^4} < 10^{-50}$.

Supersymmetry
Predicts $R_{\mu e} \sim 10^{-15}$

Compositeness

Heavy neutrino

Leptoquarks

Two Higgs doublets

New heavy bosons

New physics mechanisms, including tree-level. Probes up to 10^4 TeV scale!

Coherent Conversion

- We're **not** going to observe $> 10^{50}$ free muon decays and spot the one that is missing neutrinos.
- To probe rates down to 10^{-16} , we'll need to make 10^{18} muons. Muons are bound to a nucleus, high overlap with quarks.
- We are not detecting neutrinos or nuclear recoils, so the momentum measurement is the **only** discriminant between conversions and regular muon decay.

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

Conversion process

Ordinary muon capture

Current limit: $< 7 \times 10^{-13}$ (Sindrum II)

Mu2e can rule out: 8×10^{-17} (90% c.l.)

If $R_{\mu e} \sim 10^{-15}$, we'll see 40 events.

Single event sensitivity 3.01×10^{-17}

5σ discovery limit 2×10^{-16}

Electron Spectrum

How to Make Muons

Mu2e gets 8 GeV/c protons from the Fermilab accelerator complex.

Smash onto tungsten target: get lots of junk but a lot of charged pions.

Pions decay into muons.

Problem: the other junk is plentiful, and we want muons that will capture on Al.

Big Deal #1: Pulsed Beam

- We get short, sharp proton pulses every 1695 ns.
- Extremely good beam extinction, $< 10^{-10}$ protons outside pulse.
- Only collect data after junk has cleared out/decayed away.
- About 50% of muons capture or decay during our live window.

Big Deal #2: B-field Gradient and S-Bend Solenoid

B-field gradient reflects upstream-going particles back downstream, increasing muon yield.

Also keeps particles from getting "stuck".

S-curve with collimators selects negative muons with <80 MeV/c momentum and removes neutrals.

0.0019 muons in stopping target per proton on production target.

Transport solenoid first unit delivered to Fermilab

31 transport solenoid coils (of 52)

Test cryostat for every coil

US 10-cent coin for scale

All required superconductor has been produced.

Big Deal #3: A Holey Tracker

Design is deliberately blind to electrons with $< 55 \text{ MeV}/c$.

10^{20} muon decays, but only 10^2 reconstructed.

- Straws with 1 atm 80:20 Ar:CO₂, in vacuum.
- 12 μm 2-layer mylar straws, Au and Al coated.
- 25 μm tungsten sense wire, Au coated.
- Highly modular: can turn off wire HV in pairs, or cut off gas from 1/3 arc segments (216 total).
- $< 1\%$ radiation length for conversion electrons, mostly from straws.
- $< 180 \text{ keV}/c$ p_T resolution at $105 \text{ MeV}/c$ ($< 0.18\%$).

Students assembling tensioning fixtures.

Mockup of tracker plane assembly

X-ray scanning machine for measuring wire & straw positions

Panel with electronics mounted, in test stand

Big Deal #4: Cosmic Ray Veto

- Simulations show that cosmic ray interactions will generate 1 fake signal-like electron in the detectors each day.
- Passive shielding (e.g. putting in a mine) is unfeasible.
- Active shielding with 99.99% efficiency can ensure that we are not fooled.
- Nearly-hermetic 4-layer scintillators with double readout: a huge detector!

All scintillator (26 km!)
has been produced.

Scintillator cross section

Positioning and
retention

Other Essential Components

Production Target
Holder & Tooling

Stopping Target Foils

DAQ, slow controls, civil construction, simulation, online software, shielding...

Heat and Radiation Shield deals with 8 kW dumped inside a superconducting solenoid.

Calorimeter

Bronze casting for Heat and Radiation Shield

Calorimeter Large Prototype

Production target remote-handling fixture

Summary Plot (3 years)

Status

- Building completed, is being outfitted with supporting equipment.
- Superconductor produced, solenoids being built.
- CRV modules being produced.
- Calorimeter being built.
- Tracker straws procured, module assembly starting up.
- Physics data taking to begin in 2022
 - 1 yr commissioning, 3 years running.
- Mu2e-II Expression of Interest on ArXiv: 1802.02599

COMET

It's good to have multiple experiments to validate results!

- Very similar design concepts, same target sensitivity
- Two-stage approach

Other lepton flavour violating process experiments:

- MEG-II ($\mu \rightarrow e\gamma$) at PSI
- Mu3e ($\mu \rightarrow e e^+e^-$) at PSI

Summary

- Mu2e will improve the sensitivity to μ -e conversion in the field of a nucleus by 4 orders of magnitude. (2 orders within 2 weeks of running)
- The result can significantly inform us about new physics.
- The study is complementary to other big experiments (i.e. LHC, neutrinos...).
- We're in the construction phase.
- We're on track for data-taking in 2022!

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Backup Slides

Backgrounds

Process	Expected event yield
Cosmic rays	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
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	$0.41 \pm 0.13(\text{stat}+\text{syst})$

Mu2e Schedule

Manuscript Number: NIMA-D-18-00289

Title: The Stress Relaxation (Creep) Rate of Mu2e Straw Tubes

Article Type: Full length article

Keywords: relaxation

creep

straw tube

mu2e

mylar

Abstract: We report on the material relaxation properties of the Mu2e straw tubes measured over a period of about 5 years under two conditions. One is a fixed tension condition: two straw tubes are under a constant tension, and the lengthening of the tubes is measured as a function of time. The other is a fixed length condition: the length of four straw tubes with different initial tensions is fixed, and the tension in the tubes is measured. For the latter case, a scaling behavior appears when the ratio of the tension to the initial tension of the four straws is plotted as a function of time. In both cases, we find that the creep rates can be well parameterized with a logarithmic function of time elapsed. This implies that, for example, the amount of creep from day 20 to 200 is the same as between day 200 and 2000.

Background process: Decay in Orbit (DIO)

Michel spectrum of E_e after free muon decay, or modified in field of nucleus

Theory Predictions

After Reco Acceptance

After Reco Acceptance+ ΔE After Reco Acceptance+ ΔE +Resolution

Conversion Electron Momentum

Momentum of Muons that Stop

CLFV and Tau Decays

τ processes also suppressed in Standard Model
but less:

Lee, Shrock
Phys.Rev.D16:1444,1977

SM $\sim 10^{-49}$

$$\ln \left(\frac{m_3^2}{M_W^2} \right)^2$$

$$\left(\frac{\Delta m_{23}^2}{M_W^2} \right)^2$$

SM $\sim 10^{-14}$?

Pham, hep-ph/9810484

Good News:

Beyond SM rates can be
orders of magnitude larger
than in associated muon
decays

Bad News:

τ 's hard to produce:
 $\sim 10^{10} \tau/\text{yr}$ vs $\sim 10^{11} \mu/\text{sec}$ in
upcoming muon experiments

τ 's help pin down models and sometimes biggest BR