FERMILAB-SLIDES-19-086-E

A Search for the Neutrinoless Conversion of Negative Muons into Positrons at Mu2e

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85th Annual Meeting of the APS Southeastern Section

We are grateful for the vital contributions of the Fermilab staff and the technical staff of the participating institutions. This work was supported by the US Department of Energy; the Istituto Nazionale di Fisica Nucleare, Italy; the Science and Technology Facilities Council, UK; the Ministry of Education and Science of the Russian Federation; the National Science Foundation, USA; the Thousand Talents Plan, China; the Helmholtz Association, Germany; and the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No.690835. This document was prepared by members of the Mu2e Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

The Mu2e Collaboration

Over 200 scientists from 39 institutions

The Mu2e Collaboration, Feb 2017

Argonne National Laboratory ● Boston University Brookhaven National Laboratory ● 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 ● Lawrence Berkeley National Laboratory ● 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 Michigan ● 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

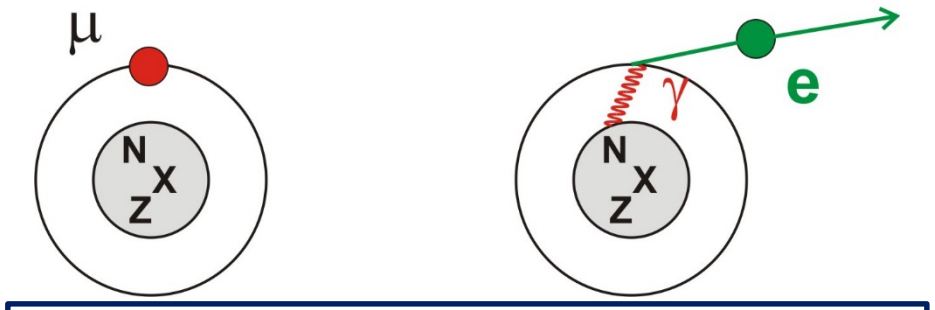
The Mu2e Experiment

- Primary Physics goal: search for $\mu^- N \longrightarrow e^- N$.
  - Charged Lepton Flavor Violation (**CLFV**)
  - Process allowed under the standard model, but at undetectable rates.
- Muons are captured by a nucleus N(A,Z) into atomic orbits.
- Muon ends up in a 1S state.
  - Normal decay: $\mu^- \longrightarrow e^- \upsilon_\mu \overline{\upsilon_e}$
  - Nuclear Capture: $\mu^- N(A,Z) \longrightarrow e^- N(A,Z)$
  - Or $\mu^- N \longrightarrow e^- N$
  - **Coherent process**: nucleus does not change
  - Conversion electron energy monochromatic:
  - $E_{\mu^- e^-} = m_\mu c^2 - B_\mu(Z) - C(A)$
    - $B_\mu(Z)$ muon binding Energy
    - C(A) recoil nucleus kinetic energy
    - Mu2e stopping ^{27}**Al** Target: $E_{\mu^- e^-} = 104.97\ MeV$
- Observation: new physics

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

SINDRUM II (Au target) $R_{\mu e} < 7 \times 10^{-13}$

muon conversion



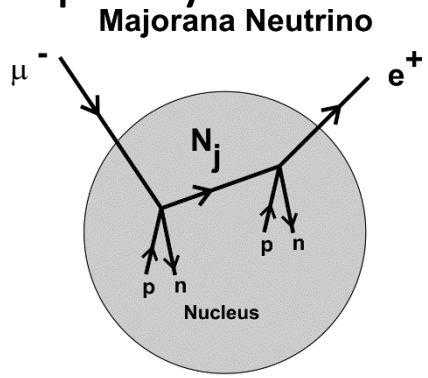
Mu2e Single Event Sensitivity 3×10^{-17}
Less than ½ background events
3 years running

Search for $\mu^- N(A,Z) \longrightarrow e^+ N(A,Z-2)$

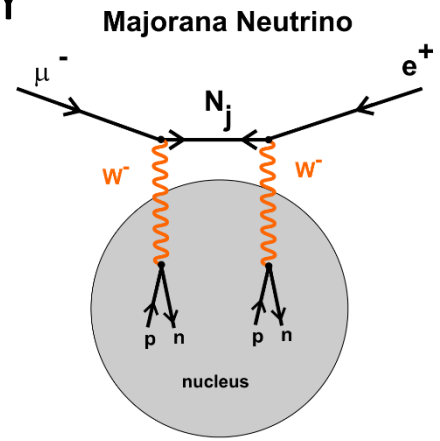
- Example of both Charged Lepton Flavor Violation (**CLFV**) and Lepton Number Violation (**LNV**).
- Most stringent limits on Lepton Number Violation double β decay: ($0\nu\beta\beta$):
  - $T_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26}\text{yr}$ for ^{136}Xe (KamLAND-Zen)
- Current limits on $\mu^- N(A,Z) \longrightarrow e^+ N(A,Z-2)$ from SINDRUM II Collaboration [Phys Lett B 422 (1998) 334-338]:
  - $\frac{\Gamma(\mu^- Ti \longrightarrow e^+ Ca^{GS})}{\Gamma(\mu^- Ti\ Capture)} < 1.7 \times 10^{-12} (90\%\ CL)$
    - Parent and daughter nucleus in Ground State (GS).
  - $\frac{\Gamma(\mu^- Ti \longrightarrow e^+ Ca^{GDR})}{\Gamma(\mu^- Ti\ Capture)} < 3.6 \times 10^{-11} (90\%\ CL)$
    - Daughter nucleus in excited state: Giant Dipole Resonance (GDR).
    - GDR 20 MeV wide: focus on ground state.
- **Not a coherent process!**

Lepton Number Violation Models

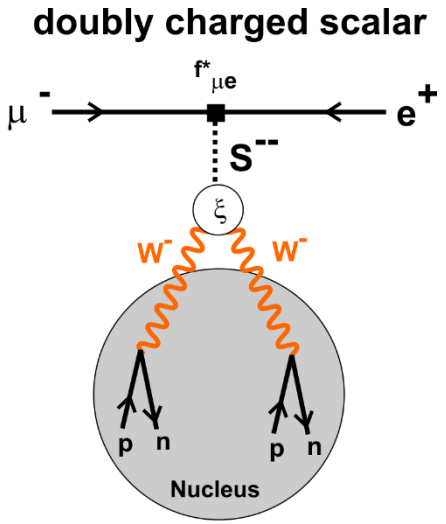
- Double charge exchange process: Involves two nucleons.
- If LNV mediated by light Majorana neutrinos
  - $0\nu\beta\beta$ rates much larger than $\mu^- \rightarrow e^+$ rates
- Other mechanisms could have $\mu^- \rightarrow e^+$ rates > $0\nu\beta\beta$ rates
  - Double charged singlet scalars: S^{--}
  - R-parity Violation SUSY



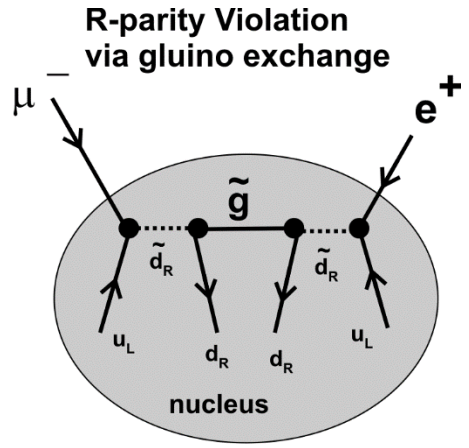
Phys Rev C 70, 065501 (2004)



Phys Rev D 95, 05509 (2017)



Phys Lett B764(2017)157
Phys Rev D 95, 055009 (2017)

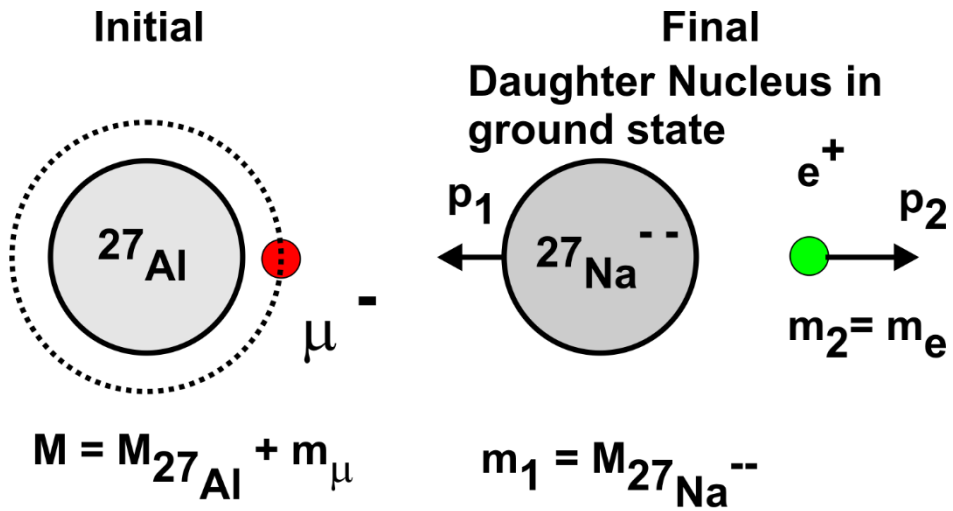


Phys Rev D 95, 05509 (2017)

- Any observation of $\Delta L = 2$ process; the neutrino has a Majorana mass (Black Box Theorem)

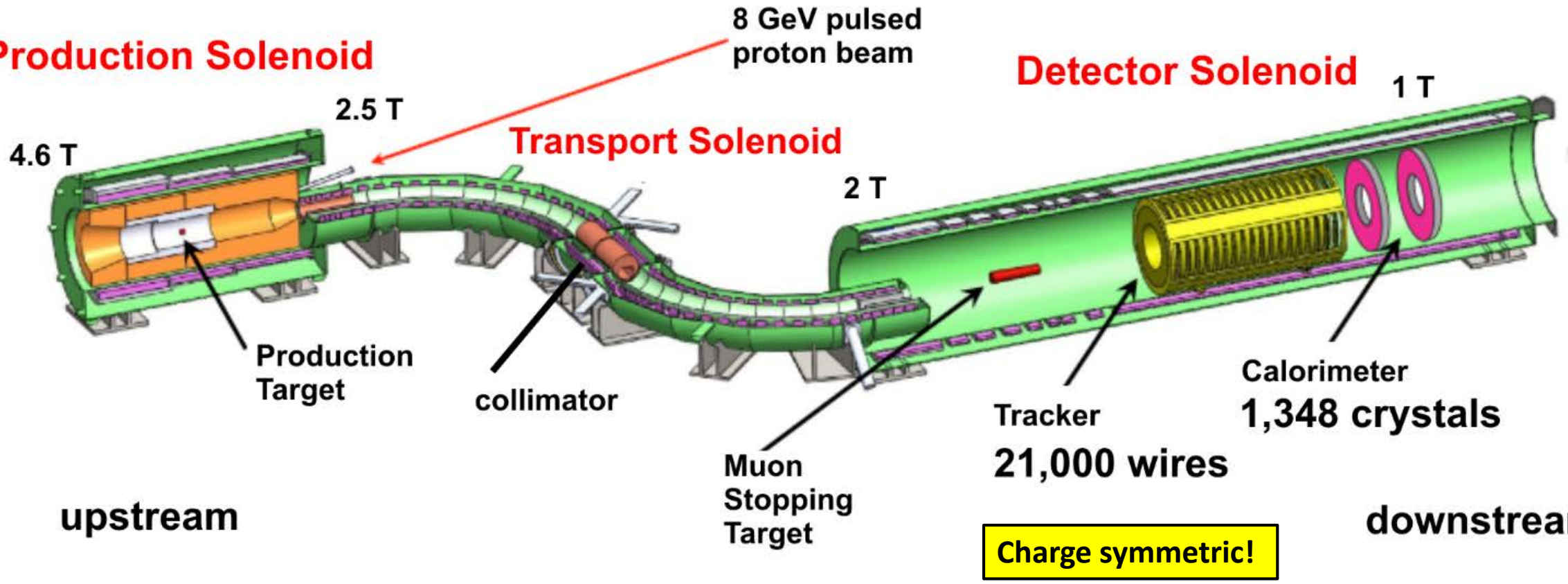
Conversion Positron Energy: Daughter Nucleus in Ground State: $\mu^- N(A,Z) \longrightarrow e^+ N(A,Z-2)$

- Mono-energetic conversion positron.
- $E_{\mu^- e^+} = m_\mu + M(A,Z) - [M(A,Z-2) + 2m_e] - B_\mu - C(A)$
- B_μ : muon binding energy.
  - Hydrogen-like atom ^1S energy level
- C(A): Kinetic energy of recoil nucleus
- Al stopping target: $E_{\mu^- e^+} = 92.32$ MeV
- According to **Nucl Phys A 767 (2006) 259-270** this process occurs 42% of time for muon to positron conversion.
  - (model dependent)



Mu2e Spectrometer

Charged particles travel in helicies

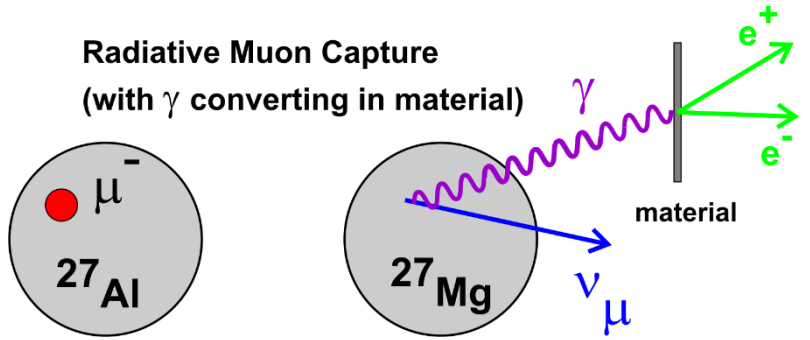


Charge symmetric!

Important Background

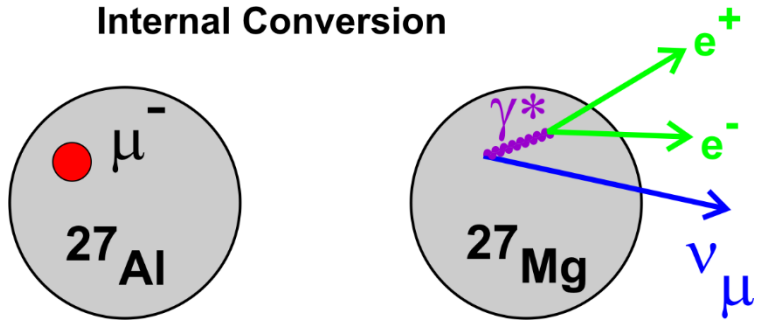
- **Radiative muon capture**
- $\mu^- N(A,Z) \rightarrow N(A,Z-1) \quad \gamma \quad \upsilon_\mu$

  $\gamma \rightarrow \quad e^+e^-$
  - For asymmetric conversion, the e^+ is reconstructed and e^- is not.
  - γ kinematic endpoint for ^{27}Al: 101.32 MeV
  - The endpoint overlaps the $\mu^- N(A,Z) \longrightarrow e^+ N(A,Z-2)$ signal (92.32 MeV).
  - Important to know the value of the end point.



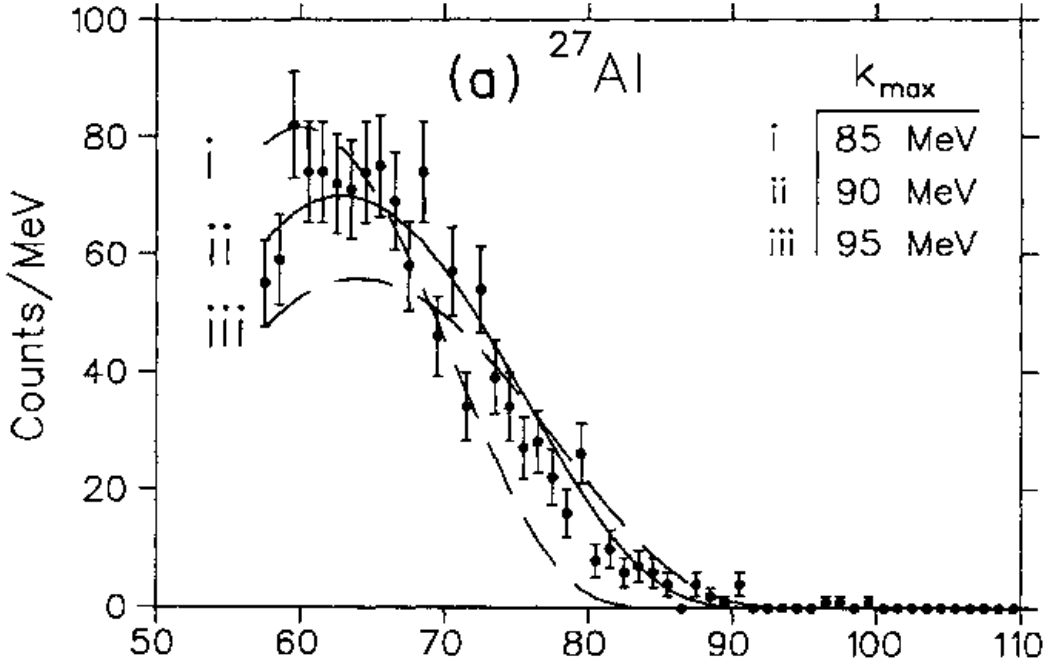
$$\mu^- p \rightarrow n \upsilon_\mu \gamma$$

- **Muon capture, internal conversion**
  - Off shell gamma is produced.
  - γ^* converts to e^+ e^- pair inside nucleus.
  - Muon internal conversion fraction is not known.
  - Using the fraction calculated from pion internal conversion.



Measurements of Radiative Muon Capture Endpoint

- Experimental measurements for endpoint vary and depend upon modeling of nuclear excited states:
  - Phys Rev C 59, 2853 (1999): 90.1 ± 1.8 MeV
  - Phys Rev C 46, 1094 (1992): 90 ± 2 MeV
- Closure approximation: final state energy is an average of all excited states.
- Mu2e would like to see a more modern calculation from the theoretical community.



D. S. Armstrong Phys Rev C 46, 1094 (1992)

Looking Ahead

- Mu2e will search for **CLFV** transition: $\mu^- N \longrightarrow e^- N$.
  - The Mu2e stopping target is ^{27}Al:
    - $\mu^- \ ^{27}Al \rightarrow e^- \ ^{27}Al$
    - Signal: mono-energetic 104.97 MeV/c electron.
    - Expect a single event sensitivity for this channel of 3×10^{-17} with less than 1/2 background event
- Mu2e will also search for the **CLFV** and **LNV** transition: $\boldsymbol{\mu^- N(A,Z) \longrightarrow e^+ N(A,Z-2)}$
  - $\mu^- \ ^{27}Al \rightarrow e^+ \ ^{27}Na$
  - Signal: mono-energetic 92.32 MeV/c positron
- Estimate of a single event sensitivity is in progress.
- Observation of either process is an indication of new physics
- Mu2e expects to take beam in 2022.