MECO
the Experiment Searching for $\mu$-e Conversion
with $10^{-17}$ Sensitivity

Masaharu Aoki
Osaka University

7th International Workshop on Neutrino Factories and Superbeams
Laboratori Nazionali di Frascati, Frascati (Rome)
June 21 - 26, 2005
Outline

- **Introduction**
  - Lepton Flavor Violation and SUSY-GUT
  - Muon-Electron Conversion ($\mu N \rightarrow e N$)
  - $\mu N \rightarrow e N$ vs. $\mu \rightarrow e \gamma$

- **MECO**
  - Learning from SINDRUM II
  - MECO features

- **MECO muon beam line**
  - Pulsed proton beam from AGS
  - Pion Production Target
  - Production Solenoid
  - Transport Solenoid
  - Detector Solenoid

- **MECO Detector**
  - Electron Tracker
  - Electron Calorimeter

- **MECO Sensitivity and Backgrounds**
Lepton Flavor Violation

- Lepton Flavor ($L_e$, $L_\mu$ and $L_\tau$) Conservation is definitely violated at least for neutral lepton sector (neutrino).

  - Extension of the Standard Model to include massive $\nu$.

- Lepton Flavor Violation (LFV) in charged lepton sector could occur through intermediate states with $\nu$ mixing. However, the expected rate is far below the experimentally accessible range; $(m_\nu^2/M_W^2)^2 \approx 10^{-60}$

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{ei}^* \right|^2 \left( \frac{m_\nu^2}{M_W^2} \right)^2 \approx 10^{-60} \left( \frac{m_\nu}{10^{-8} \text{eV}} \right)^4$$

- Many scenarios for physics beyond the SM predict sizable LFV processes in charged lepton sector.

  **Charged LFV** ↔ **Physics beyond the SM**
**SUSY-GUT and LFV**

- Large top Yukawa couplings result in sizable off-diagonal components in a slepton mass matrix through radiative corrections, and that implies observable levels of LFV in some models of SUSY-GUT.

Barbieri and Hall, 1994

**LFV diagram in SUSY-GUT**

- Study of Charged LFV is almost equivalent to the study of slepton mass matrix in a framework of SUSY-GUT.
**SUSY-GUT Prediction**

- **SU(5) SUSY-GUT Prediction**
  only a few orders of magnitude below the current experimental limit.

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Limit</th>
<th>SUSY-GUT level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu N \rightarrow e N$</td>
<td>$10^{-13}$</td>
<td>$10^{-16}$</td>
</tr>
<tr>
<td>$\mu \rightarrow e \gamma$</td>
<td>$10^{-11}$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>$10^{-6}$</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

- **SO(10) SUSY-GUT Prediction**
  enhanced by $(m_\tau/m_\mu)^2(\sim100)$ from SU(5) prediction.

*Courtesy Hisano*

![MECO single event sensitivity](image)
SUSY with RH Majorana neutrino

- SUSY + See-Saw
- Solar Neutrino
- MSW Large Angle

$\mu \rightarrow \tau \gamma$ in the MSSMRN with the MSW large angle solution

$M_\nu = 130 \text{GeV}, m_\tau = 170 \text{GeV}, m_\nu = 0.07 \text{eV}, m_\text{SM} = 0.004 \text{eV}$

Experimental bound

$M_\nu (\text{GeV})$

$\tan \beta = 3, 10, 30$
Muon Electron Conversion

• Muonic atom (1s state)

\[ \mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1) \]

• Neutrinoless muon nuclear capture

\[ \mu^- + (A, Z) \rightarrow e^- + (A, Z) \]

lepton flavors change by one unit.

– Single mono-energetic electron of \( E_{\text{max}} = (M_\mu - B_\mu) \) MeV (\( \sim \)105 MeV)
– Rate is normalized to the kinematically similar weak capture process:

\[ R_{\mu e} = \Gamma(\mu^-N\rightarrow e^-N) / \Gamma(\mu^-N\rightarrow \nu_\mu N(Z-1)) \]
\[
\mu^- N \rightarrow e^- N \quad \text{vs.} \quad \mu \rightarrow e^\gamma
\]

\(\mu^- N \rightarrow e^- N\)

• Sensitive to non-photonic process

\(\mu \rightarrow e^\gamma\)

• \(B(\mu \rightarrow e^\gamma) = 200 \times B(\mu^- N \rightarrow e^- N)\)
  for photonic process

The physics motivation is sufficiently strong for both

• \(\mu^-\) available for stopped experiment
  has been much less than that of \(\mu^+\)

• No accidental background.

• Rate-limited only in the sense that
  high detector rates will contaminate
  events and cause measurement
  errors.

Possibly different systematics, thus complementary each others.

Both should be done to maximize discovery potential

• Abundance of high intensity
  surface muons

• Rate-limited due to accidental
  background.

• Requires heroic efforts below \(10^{-14}\)
  level.
MECO Collaboration

Boston University
   R. Carey, I. Logashenko,
   J. Miller, B. L. Roberts,
Brookhaven National Laboratory
   K. Brown, M. Brennan, G. Greene,
   L. Jia, W. Marciano, W. Morse,
   P. Pile, Y. Semertzidis, P. Yamin
Berkeley
   Y. Kolomensky
University of California, Irvine
   C. Chen, M. Hebert, P. Huwe,
   W. Molzon, J. Popp, V. Tumakov
University of Houston
   Y. Cui, N. Elkhayari,
   E. V. Hungerford, N. Klantarians,
   K. A. Lan
University of Massachusetts, Amherst
   K. Kumar

Institute for Nuclear Research, Moscow
   V. M. Lobashev, V. Matushka,
New York University
   R. M. Djilkibaev, A. Mincer,
   P. Nemethy, J. Sculli
Osaka University
   M. Aoki, Y. Kuno, A. Sato
Syracuse University
   R. Holmes, P. Souder
University of Virginia
   C. Dukes, K. Nelson, A. Norman
College of William and Mary
   M. Eckhause, J. Kane, R. Welsh
Learning from SINDRUM II

- BR = 2 × 10^{-13} (2000 Gold run)
- Major background sources were
  - Muon decay in orbit
    - Requires much better resolution
  - Prompt π⁻ background
    - Requires pulsed proton beam
  - Cosmic ray background
MECO Features

• Muon Intensity
  – 1000 fold increase by using an idea from MELC at MMF
    \(10^{-2} \mu^-/P\) at 8 GeV (SINDRUM II = \(10^{-8}\), MELC = \(10^{-4}\), Muon Collider = 0.3)
    • High Z target for improved pion production
    • Graded solenoid field to maximize pion capture

• Muon Beam Quality Control
  – Muon transport in curved solenoid suppressing high momentum negatives and all positives and neutrals (new for MECO)

• Pulsed Beam  A. Baertscher et al., NPA377(1982)406
  – Beam pulse duration \(<\tau_{\mu}\)
  – Pulse separation = \(\tau_{\mu}\)
  – Large duty cycle (50%)
  – Extinction between pulses < \(10^{-9}\)

• Detector
  – Graded solenoid field for improved acceptance, rate handling, background rejection (following MELC concept)
  – Spectrometer with nearly axial components and good resolution (new for MECO)
The MECO Apparatus

- Proton Beam
- Straw Tracker
- Crystal Calorimeter
- Muon Stopping Target
- Collimators
- Superconducting Production Solenoid (5.0 T – 2.5 T)
- Superconducting Transport Solenoid (2.5 T – 2.1 T)
- Superconducting Detector Solenoid (2.0 T – 1.0 T)
- Muon Beam Stop
- Heat & Radiation Shield
Pulsed Proton Beam from AGS BNL

• AGS at BNL
  – One of the most powerful pulsed proton drivers in the world today.
• 8 GeV with $4 \times 10^{13}$ protons per second - 50kW beam power
  – Below the transition energy of AGS
  – Suppress the antiproton production
• Cycle time of 1.0 sec with 50% duty factor
• Revolution time = 2.7 $\mu$s with 6 RF buckets in which protons can be trapped and accelerated.
• Fill only 2 RF buckets for 1.35 $\mu$s pulse spacing
• $2 \times 10^{13}$ protons/RF bucket
  – twice the current bunch intensity
• Requirement: the excellent beam extinction $<10^{-9}$ protons between bunches
The extinction = $10^{-9}$ at AGS

- Quick test measurements
  - 1st test
    24 GeV with one RF bucket
    extinction < $10^{-6}$ between buckets
    < $10^{-3}$ in unfilled buckets
  - 2nd test
    7.4 GeV with one filled bucket
    extinction < $10^{-7}$

- How to improve extinction
  - 40 kHz AC dipole and 740 kHz fast kicker magnets inside AGS ring
  - RF modulated magnet and Lambertson septum magnets in primary proton transport beam line.
Pion Production Target

- High Z target material
- Minimal material in bore to absorb π/µ
- Cylinder with diameter 0.6-0.8 cm, length 16 cm
- About 5 kW of deposited energy

- Water cooling in 0.3 mm cylindrical shell surrounding target
  - Simulated with 2D and 3D thermal and turbulent fluid flow finite element analysis.
  - Temperature rise is below 100K
  - Pressure drop is acceptable (~10 atm)
  - Prototype built, tested for pressure and flow.

![Fully developed turbulent flow in 300 μm water channel](image-url)

![Graphs showing temperature and pressure drop](image-url)
The MECO Superconducting Magnets

- Magnet Conceptual Design Report (CDR) from MIT Plasma Science and Fusion Center

This presentation includes a detailed diagram of the MECO Magnets assembly, showing various components such as Axial Magnetic Load Support Rods, Gravity Support Rods, Vent & Relief Stacks, and more. The diagram provides a comprehensive view of the magnet's structure and support systems.
Production Solenoid

• Requirements
  – Capture most of pions and muons, and transport them toward detector
  – Stand up under high radiation and heat environment
    – 50kW primary proton

• Implementation
  – Axially graded magnetic field
    • 5 - 2.5 T
  – Cu and W heat and radiation shield

- 109.20 MJ stored energy
- 150 W load on cold mass
- 15 μW/g in superconductor
- 20 Mrad integrated dose
Transport Solenoid

Goals:
- Transport low energy $\mu$ to the detector solenoid
- Minimize transport of positive particles and high energy particles
- Minimize transport of neutral particles
- Absorb anti-protons in a thin window
- Minimize long transit time trajectories

Implementation
- Curved solenoid eliminate line-of-sight transport of photons and neutrons.
- Toroidal sections causes particles to drift out of plane; used to sign and momentum select beam.
- $dB/dS < 0$ for straight section to avoid reflections which would cause long transit time trajectories.
Function of the Curved Solenoid

- Particle drifts in torus magnetic fields

JD Jackson, *Classical Electrodynamics*

\[ D = \frac{1}{0.3B} \times \frac{s}{R} \times \left( \frac{p_\perp^2 + \frac{1}{2}p_z^2}{p_z} \right) \]

- Curvature drift
- Gradient drift

Charge and momentum selection
Muon Yield

- Monte Carlo calculation
  - GEANT3
  - Including original data models based on a measured pion production on similar targets at similar energy.
  - Decays, interactions, and magnetic transport included.

![Muon Momentum Distribution](chart)

- Relative yield
- Muon Momentum [MeV/c]
- Stopping Flux
- Total flux at stopping target
- 0.0025 $\mu^-$ stops/proton
Detector Solenoid

- Graded field in front section to increase acceptance and reduce cosmic ray background.
- Uniform field in spectrometer region to minimize corrections in momentum analysis.
- Tracking detector downstream of target to reduce rates from photons and neutrons.

Tracker Goal
- Excellent momentum resolution; 900 keV FWHM ($\Delta p/p=0.3\%$), Essential to eliminate muon decay in orbit background.
- High rate capability; 500kHz in individual detector elements

Calorimeter Goal
- Used for on-line Trigger
- Energy resolution ~ 5%
Spectrometer Performance

- Tracker: Axially aligned straw tubes in vacuum
  - 5mm$^\phi$, 2.5m$L$, 25µm$^t$

- Transverse direction: 0.2mm(rms) by drift time measurement
- Axial direction: 1.5mm(rms) by cathode pads on the exterior of the straws

GEANT3 Monte Carlo
- Resolution dominated by
  - Energy loss in muon stopping target; 636 keV FWHM
  - Tracker intrinsic resolution; 353 keV FWHM
    - Geometrical acceptance ~50% (60°-120°)
- Alternate transverse geometry has similarly good tracking performance with sophisticated fitting.
Electron Calorimeter

- Provides prompt signal proportional to electron energy for use in online event selection
- Provides position measurement to confirm electron trajectory
- Energy resolution ~ 5% and spatial resolution ~1 cm
- Consists of 4 vanes extending radially from 0.39 m to 0.69 m and 1.5 m along the beam axis
- ~2000 3 cm x 3 cm x 12 cm (PbWO$_4$ or BGO) crystals with APD readout
- Small arrays currently being studied for light yield, APD evaluation, electronics development
### Contributions to the Signal Rate

<table>
<thead>
<tr>
<th>Source</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time (s)</td>
<td>10^7</td>
</tr>
<tr>
<td>Proton flux (Hz) (50% duty factor, 740 kHz μ-pulse)</td>
<td>4 × 10^{13}</td>
</tr>
<tr>
<td>μ entering transport solenoid / incident proton</td>
<td>0.0043</td>
</tr>
<tr>
<td>μ stopping probability</td>
<td>0.58</td>
</tr>
<tr>
<td>μ capture probability</td>
<td>0.60</td>
</tr>
<tr>
<td>Fraction of μ capture in detection time window</td>
<td>0.49</td>
</tr>
<tr>
<td>Electron trigger efficiency</td>
<td>0.90</td>
</tr>
<tr>
<td>Fitting and selection criteria efficiency</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Single Event Sensitivity**

<table>
<thead>
<tr>
<th>μ capture probability</th>
</tr>
</thead>
</table>

### Source of Background

- **Background calculated for 10^7 s running with sensitivity of a single event for R_{μe} = 2 × 10^{-17}**
- **Sources of background will be determined directly from data.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ decay in orbit</td>
<td>0.25</td>
<td>S/N = 4 for R_{μe} = 2 × 10^{-17}</td>
</tr>
<tr>
<td>Tracking errors</td>
<td>&lt; 0.006</td>
<td></td>
</tr>
<tr>
<td>Radiative μ decay</td>
<td>&lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>Beam e⁻</td>
<td>&lt; 0.04</td>
<td></td>
</tr>
<tr>
<td>μ decay in flight</td>
<td>&lt; 0.03</td>
<td>No scattering in target</td>
</tr>
<tr>
<td>μ decay in flight</td>
<td>0.04</td>
<td>Scattering in target</td>
</tr>
<tr>
<td>π decay in flight</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Radiative π capture</td>
<td>0.07</td>
<td>From out of time protons</td>
</tr>
<tr>
<td>Radiative π capture</td>
<td>0.001</td>
<td>From late arriving pions</td>
</tr>
<tr>
<td>Anti-proton induced</td>
<td>0.007</td>
<td>Mostly from π⁻</td>
</tr>
<tr>
<td>Cosmic ray induced</td>
<td>0.004</td>
<td>10^{-4} CR veto inefficiency</td>
</tr>
<tr>
<td>Total Background</td>
<td>0.45</td>
<td>With 10^{-9} inter-bunch extinction</td>
</tr>
</tbody>
</table>

5 signal events with 0.5 background events in 10^7 s running if R_{μe} = 10^{-16}
Summary

• Muon-electron conversion is definitely a “must do” experiment. The discovery will be right down there only a few orders of magnitude below the current experimental limit.

• The physics output from the muon-electron conversion is very robust. Many different types of theoretical models beyond SM can be studied with this process.

• The discovery potential of MECO is MAXIMUM:
  – 1000 fold increase of the $\mu^{-}$ stops in the target; 0.0025 $\mu^{-}$ stops/proton.
  – Well designed beam line, which minimizes the beam contamination while maintains maximum muon yield.
  – Large detector acceptance with good resolution.

\[ R_{\mu\ell} = 2 \times 10^{-17} \]

• Waiting for budget approval. After 65 weeks of the magnet construction, the experiment will run.