A search for the muon to electron conversion at J-PARC: COMET Experiment

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on behalf of the COMET Collaboration
Windows on the Universe, Quy Nhon, Vietnam, 8th August 2018

Outline
• Physics Motivations
• COMET Experiment
• Summary
Charged Lepton Flavor Violation = new physics

Flavors are mixed through CKM matrix in the Standard Model,
Already confirmed $\rightarrow$ Novel Prize in 2008

Flavors are mixed through PMNS matrix, Already confirmed (extension of SM) $\rightarrow$ Novel Prize in 2015

Charged Lepton Flavor Violation
Strongly restricted in the Standard Model,
Not observed so far $\rightarrow$ Discovery = New Physics
What & Why $\mu$-e conversion?

- Muon to electron conversion in nuclei w/o neutrinos
  - $\sim O(10^{-54})$ in SM + $\nu$-oscillation
  - Enhanced in many BSMs
  - Highly sensitive to New Physics
- Simple kinematics: $E_e = M_\mu - B_\mu - E_{\text{recoil}} \sim 105\text{MeV} \ @\text{Al}$
- Easy to get high statistics due to its long lifetime (880ns @Al)
- LHC, other CLFV searches, muon g-2, b-physics are complementary
- Current upper limit: $7 \times 10^{-13}$ (90% C.L.) by SINDRUM II
μ-e conversion in BSM

- μ-e conversion appears in many physics models beyond the standard model (BSM)
  - Just requires an additional inter-mediating particle(s) that allow lepton flavor changing
- In most cases, branching ratio(BR) can be detectable
  - BR varies depending on the models and parameters
  - Detection = Discovery of new physics
  - Measurement = Specification of new physics!

Requirements

- **High statistics**
  - $>10^{18-20}$ of stopping muons are required
    - High intensity proton beam & Effective muon production/collection
- **Background suppression**
  - **Intrinsic BG**: Muon DIO (Decay In Orbit)
    - Good momentum resolution = Less multiple scattering
  - **Beam BG**: Radiative $\pi$ capture, $\pi/\mu$ decay in flight, Antiproton, Proton leakage, etc.
    - Pulse beam + off-time measurement, strong pion suppression
    - Good extinction* factor ($<10^{-10}$)
  - **Other BG**: Cosmic ray
    - Adding veto detector

  \[ \text{Extinction} = \frac{\text{Number of protons between 2 bunches}}{\text{Number of protons in a bunch}} \]
J-PARC

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

Materials and Life Science Experimental Facility

Hadron Beam Facility

MR Synchrotron (0.75 MW)*

Neutrino to Kamiokande

3 GeV Rapid Cycle Synch. (25 Hz, 1MW)

Linac (330m)

Nuclear Transmutation (Phase 2)
Proton Beam for COMET

- Bunched slow extraction with a 3.2(56) kW accelerator operation in Phase-I(Phase-II)
- Pulsed beam with 1.2μs intervals can be realized by emptying one of the two buckets in RCS
- Accelerate protons up to 8GeV in MR → Deliver them to COMET hall @ HD Facility
- Extinction has been recently measured to be $10^{-11}$~$10^{-12}$ in FX ($<6 \times 10^{-11}$ in SX)
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COMET Overview

- **Aiming $O(10^{-17})$ sensitivity**
  - 10,000 times better than the current limit
- C-shaped muon transport solenoid
  - For suppress beam BG
- Additional curved Electron spectrometer
  - Suppress DIO+beam BG

**Muon Stopping Target**
- + beam blocker

**Production Target + Pion Capture Solenoid**
- ~5T, Large aperture to effectively collect low momentum $\pi/\mu$

**8GeV Proton Beam**
- Muon Transport Solenoid ~3T
  - to select low momentum $\mu$- and suppress $\pi$-

**Electron Spectrometer**
- ~1T
  - to select ~100MeV/c charged particles

**Detector Solenoid**
- ~1T
• Construct the first 90° of the muon transport solenoid
• Perform the \( \mu \)-\( e \) conversion search with a sensitivity of \( 10^{-15} \) using CyDet
• Measure the beam directly using StrECAL as a Phase-II prototype detector
Muon Beam/Target

- Muon transported in a curved solenoid w/ a dipole field
  - Reduce pions which can produce high momentum secondaries
  - Momentum/charge selection
- Muons stopped inside the series of 200μm thin aluminum disks
  - Stopping rates are \( \sim 5 \times 10^{-4} (1.6 \times 10^{-3}) / \text{POT (=a Proton On Target)} \) in Phase-I (Phase-II)

Saddle type coil is put outside of each solenoid coil to generate dipole field.

Muon stopping target in Phase-I.
CyDet

- **Cylindrical Drift Chamber (CDC)**
  - Main tracker for Phase-I physics measurement
  - All stereo wires to reconstruct 3D trajectories
  - 20 layers with ~5k/15k sense/field wires
  - Gas mixture, He:iC₄H₁₀=90:10
  - \( \sigma_p \sim 200 \text{ keV/c} @105\text{MeV/c} \), is required
  - Detector has been constructed & performance study with cosmic-rays is ongoing

- **Cherenkov Trigger Hodoscope (CTH)**
  - Each module consists of an acrylic Cherenkov radiator and a plastic scintillator
  - 48 modules arranged both up/downstream
  - Require 4 hits coincidence to suppress the accidental trigger due to \( \gamma \) rays
  - **Better than 1 ns time resolution** is already obtained

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**StrWTracker**

- **20/12μm** thin straw tubes with diameters of 10/5mm, operational in vacuum, for Phase-I/II
- Precise position/momentum measurement ($\sigma_x<200$μm, $\sigma_p=150-200$keV/c @105MeV/c e-)
- Mass production of phase-I Straw tubes was completed, ready for the detector construction!

**ECAL**

- Array of 2,000 LYSO crystals
- Fast decay time (~40ns), good energy resolution (<5% @105MeV/c e-), High density (7.2g/cm$^3$)
- Performance study is almost completed, start purchasing the crystals
Phase-I Single Event Sensitivity

<table>
<thead>
<tr>
<th>Event selection</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Online event selection efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>DAQ efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Track finding efficiency</td>
<td>0.99</td>
</tr>
<tr>
<td>Geometrical acceptance + Track quality cuts</td>
<td>0.18</td>
</tr>
<tr>
<td>Momentum window ($\varepsilon_{\text{mom}}$)</td>
<td>0.93</td>
</tr>
<tr>
<td>Timing window ($\varepsilon_{\text{time}}$)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.041</strong></td>
</tr>
</tbody>
</table>

$$B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) = \frac{1}{N_\mu \cdot f_{\text{cap}} \cdot f_{\text{gnd}} \cdot A_{\mu-e}}$$

- Number of muons stopped inside targets
- Fraction of $\mu$-$e$ conversion to the ground state = 0.9
- Fraction of muons to be captured by Al target = 0.61

- $3 \times 10^{-15}$ S.E.S. is achievable within ~150 days of DAQ time
  - Corresponding to $N_\mu = 1.5 \times 10^{16}$ (= $3 \times 10^{19}$ POT)

$103.6 < p_e < 106.0$ MeV/c
$700 < t_e < 1170$ ns
# Phase-I Backgrounds

<table>
<thead>
<tr>
<th>Type</th>
<th>Background</th>
<th>Estimated events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>Muon decay in orbit</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Radiative muon capture</td>
<td>0.0019</td>
</tr>
<tr>
<td></td>
<td>Neutron emission after muon capture</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Charged particle emission after muon capture</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Prompt Beam</td>
<td>* Beam electrons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Muon decay in flight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Pion decay in flight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Other beam particles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All (*) Combined</td>
<td>≤ 0.0038</td>
</tr>
<tr>
<td></td>
<td>Radiative pion capture</td>
<td>0.0028</td>
</tr>
<tr>
<td></td>
<td>Neutrons</td>
<td>~ 10^{-9}</td>
</tr>
<tr>
<td>Delayed Beam</td>
<td>Beam electrons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muon decay in flight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pion decay in flight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radiative pion capture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anti-proton induced backgrounds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cosmic rays†</td>
<td>≤ 0.01</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.032</td>
</tr>
</tbody>
</table>

† This estimate is currently limited by computing resources.

- Normalized to a $3 \times 10^{-15}$ of S.E.S., assuming extinction factor $= 3 \times 10^{-11}$
- Background is almost negligible
- To be measured directly in Phase-I beam measurement

COMET Phase-II

• In comparison with Phase-I...
  • Beam power: 3.2kW $\rightarrow$ 56kW ($\times$18)
    ➥ Longer muon transportation enables to use more powerful proton beam
  • Muon stopping rate (per POT): $5 \times 10^{-4} \rightarrow 1.6 \times 10^{-3}$ ($\times$3)
    ➥ Replacement of production target from Graphite to Tungsten, longer transportation solenoid
  • Total signal acceptance: 0.04 $\rightarrow$ 0.06 ($\times$1.5)
    ➥ Larger detector acceptance (covers the most of forward direction)
  • Momentum resolution will be improved: $\sim 200\text{keV/c} \rightarrow 160-180\text{keV/c}$ ($\sim 10\%$)
    ➥ Less materials in tracker: CDC $\rightarrow$ thin straw tube tracker in vacuum
Phase-II Sensitivity & Backgrounds

- Assuming 0.5 year of DAQ time (20% longer than in Phase-I)
  - Total statistical improvement is calculated to be $100$!
  - $3 \times 10^{-17}$ S.E.S. is achievable in 0.5 year, or $2.7 \times 10^{-17}$ in 200 days
- Nevertheless, BG rate will be low enough based on the simulation study

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Background Rate per $\mu^-$ stop</th>
<th>Background Rate per POT</th>
<th>Background Rate per second</th>
<th>Total Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>DIO</td>
<td>$6.20 \times 10^{-20}$</td>
<td>$9.92 \times 10^{-23}$</td>
<td>$4.31 \times 10^{-9}$</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>RMC</td>
<td>$3.73 \times 10^{-31}$</td>
<td>$6.01 \times 10^{-34}$</td>
<td>$2.61 \times 10^{-20}$</td>
<td>$4.10 \times 10^{-13}$</td>
</tr>
<tr>
<td>Delayed</td>
<td>RPC</td>
<td>–</td>
<td>$1.73 \times 10^{-27}$</td>
<td>$7.51 \times 10^{-14}$</td>
<td>$1.18 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Beam</td>
<td>–</td>
<td>$1.47 \times 10^{-24}$</td>
<td>$6.39 \times 10^{-11}$</td>
<td>$1.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Stopped $\bar{p}$</td>
<td>–</td>
<td>$4.34 \times 10^{-22}$</td>
<td>$1.89 \times 10^{-8}$</td>
<td>0.296</td>
</tr>
<tr>
<td></td>
<td>$\pi^-$ from $\bar{p}$</td>
<td>–</td>
<td>$1.95 \times 10^{-30}$</td>
<td>$8.49 \times 10^{-17}$</td>
<td>$1.33 \times 10^{-9}$</td>
</tr>
<tr>
<td>Prompt</td>
<td>RPC</td>
<td>–</td>
<td>$1.82 \times 10^{-24}$</td>
<td>$7.91 \times 10^{-11}$</td>
<td>$1.24 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Beam</td>
<td>–</td>
<td>$2.80 \times 10^{-24}$</td>
<td>$1.22 \times 10^{-10}$</td>
<td>$1.91 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\pi^-$ from $\bar{p}$</td>
<td>–</td>
<td>$3.56 \times 10^{-29}$</td>
<td>$1.55 \times 10^{-15}$</td>
<td>$2.43 \times 10^{-8}$</td>
</tr>
<tr>
<td>Cosmics</td>
<td>–</td>
<td>–</td>
<td>$1.87 \times 10^{-8}$</td>
<td>–</td>
<td>$0.294$</td>
</tr>
<tr>
<td>Total</td>
<td>–</td>
<td>–</td>
<td>$4.22 \times 10^{-8}$</td>
<td>–</td>
<td>$0.662$</td>
</tr>
</tbody>
</table>

$\leftarrow$ DIO in signal region  
$\leftarrow$ Electron from Radiative Muon Capture  
$\leftarrow$ Anti-proton rate is estimated conservatively  
$\leftarrow$ Electron rate from cosmic-rays is estimated conservatively
Summary

• CLFV processes are predicted by many BSMs while they’re strongly suppressed in the Standard Model
• COMET aims to search for $\mu$-e conversion with unprecedented S.E.S. of $3 \times 10^{-15}$ ($< 10^{-16}$) in Phase-I (Phase-II) @J-PARC
  • There is a huge discovery potential
• Phase-I experiment has been already approved by J-PARC PAC
  • All detectors are being prepared on schedule
  • Facility/beam-line are under construction in parallel
• Detector will be ready in 2019 for Phase-I, start soon after completing the beam-line construction
• Phase-II will follow Phase-I to reach 100 times better sensitivity than in Phase-I
  • Almost all R&Ds for Phase-II will be completed in Phase-I
  • Further information can be found at http://comet.kek.jp/Introduction.html

⇒ Stay tuned!
Backup