Search for Muon to Electron Conversion at J-PARC - the COMET Experiment -

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Flavor Physics

- Precise measurement of flavor structure
- Establishment of SM
- Indication of BSM?
  - muon g-2, proton radius, B leptonic decay ···
Branching Ratio UL

- Cosmic μ
- π-beam
- μ-beam

- μ → eγ
- μ → 3e
- μN → eN

MEG
4.2 x 10^{-13}

Year

Bernstein & Cooper
cLFV Searches using muon

- No sign of new physics from High Energy Frontier experiments so far
- Survey a large area in high energy region using forbidden process in SM with extremely large statistics
  - Role of Flavor Physics
- No SM background in muon LFV process
- Intense muon beam at high-power proton machines

\[
\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c.
\]

\[
\frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \bar{f}_\gamma \mu f + h.c.
\]

Final States

- \text{e} \rightarrow \gamma\text{e}
- \text{eee}
- \text{e}
More Muons!

- Muons are produced from pion decays
- More muons produced in more pion decays
- Pion production yield depends on the power the proton driver
  - High-Power machine rather than High-Energy machine
  - Proton current
μ-e conversion search

- Atomic capture of $\mu^-$
  - Decay in orbit (DIO)
  - Electron gets recoil energy
- Capture by nucleus
  - Resultant nucleus is different
- $\tau_{\mu^N} < \tau_{\mu}^\text{free}$ ($\tau_{\mu}^\text{Al} = 860\,\text{nsec}$)

- $E_{\mu e}(\text{Al}) \sim m_\mu - B_\mu = 105\,\text{MeV}$
  - $B_\mu$: binding energy of the 1s muonic atom
- $\mu^-$-$e$ conversion

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

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

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$
Experimental Techniques

- Process: $\mu^{-}+(A,Z) \rightarrow e^{+}+(A,Z)$
  - A single mono-energetic electron
    - $E_{\mu e} \sim m_{\mu} - B_{\mu} : 105 \text{ MeV for Al}$
  - Delayed: $\sim 1 \mu \text{s}$
  - No accidental backgrounds

- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_{e} > 102.5 \text{ MeV (BR: } 10^{-14})$
    - $E_{e} > 103.5 \text{ MeV (BR: } 10^{-16})$
  - Beam Pion Capture
    - $\pi^{-}+(A,Z) \rightarrow (A,Z-1)^{*} \rightarrow \gamma+(A,Z-1)$
      - $\gamma \rightarrow e^{+} e^{-}$

$$R_{\text{ext}} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$
Mu-e Conversion

Electron Energy Spectrum

run2000 on gold

SINDRUM II

BR[\(\mu^- + \text{Au} \rightarrow e^- + \text{Au}\)] < 7 \times 10^{-13}
Mu-e Conversion Search Experiments

- DeeMe
  - ~10^{-13}-14 using C or SiC for muonic atom formation

- COMET Phase-I & II
  - Al target to reach the 10^{-14} sensitivity in Phase-I and 10^{-16} in Phase-II

- Mu2e
  - Al target to reach the 10^{-16} sensitivity
J-PARC Facility (KEK/JAEA)

LINAC
400 MeV

Rapid Cycle Synchrotron
Energy: 3 GeV
Repetition: 25 Hz
Design Power: 1 MW

Main Ring
Max Energy: 30 GeV
Design Power for FX: 0.75 MW
Expected Power for SX: > 0.1 MW
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Neutrino beam to Kamioka
J-PARC Facility
(KEK/JAEA)

Neutrino beam to Kamioka

Material and Life Science Facility

Nuclear and Particle Physics Exp. Hall

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COMET at J-PARC

- Target S.E.S. $2.6 \times 10^{-17}$
  - Pulsed proton beam at J-PARC
    - Insert empty buckets for necessary pulse-pulse width
    - bunched-slow extraction
  - Pion production target in a solenoid magnet
  - Muon transport & electron momentum analysis using C-shape solenoids
    - smaller detector hit rate
    - need compensating vertical field
  - Tracker and calorimeter to measure electrons
  - Recently staging plan showed up. The collaboration is making an effort to start physics DAQ as early as possible under this.
    - Phase-I 8GeV-3.2kW, $< 10^{-14}$
    - Phase-II 8GeV-56kW, $< 10^{-16}$
COMET Phase I & II

- Phase I
  - Beam background study, achieve an intermediate sensitivity of $< 10^{-14}$
  - 8GeV, 3.2kW, 150 days of DAQ

- Phase II
  - 8GeV, 56kW, 1 year DAQ to achieve the COMET final goal of $< 10^{-16}$ sensitivity
COMET Phase-I Status
COMET Primary Beamline
Beamline
Solenoid Magnet System

- Capture solenoid: Coil winding & cold mass assembly in progress. Cryostat design ongoing
- Transport solenoid: Installed and ready for cryogenic test
- Bridge & detector solenoids: design in progress.
- Cryogenic System: Refrigerator test completed. Helium transfer tube in production
Phase-1 Detector

Stage-2

Precise check

Elect. trigger upgrade &
Detail performance check

Track Reconstruction

Hit selection & Hough Transformation

Detector solenoid
Beam collimator
Transport solenoid
Capture solenoid -5T
Proton beam
muons
Radiation shield
Pion production target

COMET Phase-1 Detector

36 RECBEs
Phase I Detector cont’d

Detector for beam BG measurement in Phase I and physics measurement in Phase II

- LYSO cryostat production in progress
- Electronics design (almost) finalized

Prototype straw tracker for performance evaluation

13 tubes broken out of 2700
- After two-years storage
  - Epoxy crystallization etc.
Other R&D

- Intensive studies of radiation hardness
- Aluminum muon stopping target design & X-ray monitoring
- New development of a proton beam monitor
- Cosmic-ray veto system
- Simulation and analysis tool development
- 8GeV acceleration & beam extinction factor measurement
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8GeV Acceleration & Extraction

- 8GeV acceleration and extraction to the abort line (FX) and Hadron Hall (SX)
  - 4 bunches out of 9 bunches are filled with protons to realize the COMET beam time structure
    - Same number of protons per bunch with that of Phase I beam
    - Injection kicker timing is shifted to kick in only the filled bunch
    - SX with RF HV on to keep the bunched time structure

RCS

Hadron Hall Primary Target

100ns

(30GeV operation)
$R_{\text{ext}}$ at the abort line (FX)

Extinction at MR Abort w/ FX (2018)

- Excellent extinction of $10^{-12} \sim 10^{-11}$ is obtained = Good enough for COMET !!
- A strong dependence on beam condition (tune, beam loss) is observed.
R_{ext} in Hadron Hall (SX)

- Extracted pulsed proton beam injected to the Hadron Primary target and produced secondary beam transport to K1.8 area
- Secondary beam time structure measurement with a hodoscope
- Proton leakage is appeared in **K4_rear only** within very early extraction timing (<0.1 sec)
- No leakage is appeared in other region
- By rejecting <0.1 sec events, upper limit of extinction is obtained: <6.0 x 10^{-11}
- Good enough for COMET though we need further studies on K4_rear leakage

**w/o kicker shift = initial extinction**

**w/ kicker shift = improved extinction**

- Ion Chamber
- Hodoscope
- Trig. Counters
Summary

- Muon flavor physics experiment is a clue to investigate new physics BSM
- High-power proton driver to produce high-intensity muon beam
- COMET intends to improve the sensitivity to the mu-e conversion process by more than a factor of 10,000 in two steps;
  - Phase-I sensitivity < $10^{-14}$
  - Phase-II sensitivity < $10^{-16}$
- J-PARC MR operation at 8GeV to provide the proton beam
  - Proton beam extinction factor as good as $6 \times 10^{-11}$ confirmed. Need further improvement in collaboration with the J-PARC accelerator group
- Pion/muon capture system, muon transport system as well as the physics detector in preparation
- Collaboration is expanding even now! Any young student and researcher is welcome to join the collaboration!!