Search for Muon to Electron Conversion at J-PARC MLF

The Current Status of DeeMe Experiment

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Outline

- Physics Motivation
- DeeMe Experiment
- Current Status
  - Beamline
  - Spectrometer Magnet
  - Detector
  - After-Proton Measurement
  - Muon Production Target
- Summary & Prospects
Physics Motivation

DeeMe Experiment

Current Status
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- Muon Production Target

Summary & Prospects
Lepton Flavor Violation is forbidden in the original Standard Model.

Neutrino oscillation = Flavor Violation of neutral lepton

Charged Lepton Flavor Violation (CLFV)

- process: $\mu \rightarrow e\gamma$, $\mu \rightarrow e e e$, $\mu N \rightarrow e N$
  ... not observed yet

CLFV induced by neutrino flavor mixing

\[
\text{BR}(\mu \rightarrow e\gamma) = (\Delta m_{\nu ij}^2 / M_W^2)^2 \sim 10^{-50}
\]

too small to be observed experimentally in the framework of the Standard Model

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experimental observation of CLFV process

||

clear evidence of the new physics beyond the Standard Model
CLFV in muon

Theoretical models beyond the Standard Model
( SUSY-GUT, SUSY-seesaw, Doubly Charged Higgs, etc.. )

sizable branching ratio of CLFV

predicted branching ratio = $10^{-14} \sim 10^{-18}$ (ex. SUSY-GUT)

Current upper limit from experiments

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- N \rightarrow e^- N$</td>
<td>SINDRUM-II: $\text{BR}(\mu^- \text{Au} \rightarrow e^- \text{Au}) &lt; 7 \times 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>SINDRUM-II: $\text{BR}(\mu^- \text{Ti} \rightarrow e^- \text{Ti}) &lt; 4.3 \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>TRIUMF: $\text{BR}(\mu^- \text{Ti} \rightarrow e^- \text{Ti}) &lt; 4.6 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ \gamma$</td>
<td>MEG: $\text{BR}(\mu^+ \rightarrow e^+ \gamma) &lt; 4.2 \times 10^{-13}$ (new!)</td>
</tr>
</tbody>
</table>

The discovery is right around the corner.

$\Rightarrow$ A new experimental search with sensitivity under $10^{-13}$ should be started in a timely manner.
Muon to Electron Conversion in the Nuclear Field

**Decay-In-Orbit (DIO)**

\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

**Muon Capture**

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

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**μ - e conversion** (CLFV)

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

- mono-energetic signal electron (\(\sim 105 \text{ MeV/c}\))
- no accidental backgrounds

**Backgrounds**

- **Decay-In-Orbit**
  - nucleus recoil ... higher tail extended
  - signal momentum
  - the most important BG.

- **Radiative Pion Capture** ← *prompt timing*
  \[ \pi^- + N(A,Z) \rightarrow N(A,Z-1)^* \]
  \[ \rightarrow \gamma + N(A,Z-1), \quad \gamma \rightarrow e^+ e^- \]

- Beam related BG (After-Proton)
Effective Lagrangian

\[ \mathcal{L} = \frac{1}{1 + \kappa \Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{1 + \kappa \Lambda^2} \left( \bar{\mu}_L \gamma^\mu e_L \right) \left( \bar{q}_L \gamma_\mu q_L \right) \]

\[ \Lambda (\text{TeV}) \]

\[ \mu - e \text{ conversion in the nuclear field} \]

... sensitive to both photonic and non-photonic processes
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new $\mu - e$ conversion search, DeeMe at J-PARC Material and Life Science Experimental Facility (MLF)

MLF primary proton beam

- 3 GeV, 500 kW → will be upgraded to 1 MW.

muon production target → 4 beamlines (MUSE)

neutron production target → more than 20 beamlines
MLF MUSE

J-PARC MLF Muon Science Establishment (MUSE)

S Line
surface $\mu^+$ beam (30 MeV/c)
material science

3GeV proton beam

muon target

U Line
ultra slow $\mu^+$ beam (0.05-60 keV)
material science

D Line
surface $\mu^+$ beam (30 MeV/c)
decay $\mu^+/\mu^-$ beam (5-120 MeV/c)
material science
in operation for users' experiment
J-PARC MLF Muon Science Establishment (MUSE)

**H Line**

- for fundamental physics
- multipurpose beamline
  - $\mu$-e conversion search (DeeMe)
  - muonium hyperfine splitting
  - $g$-2/EDM
  - muon microscopy

conceptual design by Jaap Doornbos (TRIUMF)
beam energy = 3 GeV

\[ p \text{ production threshold} \]
\[ \Rightarrow \text{no } p \text{ induced backgrounds} \]

• fast extracted beam
  no off-timing proton
  \[ \Rightarrow \text{no prompt background at time window} \]
Concept of DeeMe

1. π⁻ Production
2. in-flight π⁻ → μ⁻
3. Muonic Atom Formation
4. μ⁻e Conversion
= $\mu^-$ stopping target
utilize muonic atoms
formed in the production target

NO $\pi^-$ decay volume
NO additional stopping target
conventional $\mu$–e search
Principle of Experiment

Concept of DeeMe

1. π⁻ Production
2. in-flight π⁻ → μ⁻
3. Muonic Atom Formation
4. μ-e Conversion

- transport signal electrons (105 MeV/c)
- Beam optics is optimized for signal electrons.

⇒ momentum selection
⇒ suppress low momentum backgrounds
Concept of DeeMe

1. $\pi^-$ Production
2. in-flight $\pi^- \rightarrow \mu^-$
3. Muonic Atom Formation
4. $\mu$-e Conversion

Principle of Experiment

- momentum analysis
- identify signal electrons
- DIO spectrum

*spectrometer magnet & tracking device (MWPC)
Full utilization of existing facility (high quality beam from RCS, muon target, etc)

... Early realization of the experiment

new physics result in timely manner
Performance of H Line

- Transmission Efficiency
  - simulated by G4BEAMLINE
  - beam optics
    * optimized for signal electron (105MeV/c)
  - acceptance at the spectrometer
    as a function of momentum

- Acceptance $\frac{Sr}{(MeV/c)}$
  - $\sim 120\ mSr/(MeV/c)$ @ signal momentum
  - $\Rightarrow$ Higher sensitivity than ever before
- wide range acceptance (90 – 120 MeV/c)
  $\Rightarrow$ Background monitoring
Sensitivity, Backgrounds

**Single Event Sensitivity**
- 1-year run ($2 \times 10^7$ sec), with 1 MW beam, H Line acceptance ...

\[ 1.2 \times 10^{-13} \text{ for Carbon Target} \]

\[ 2.1 \times 10^{-14} \text{ for SiC} \]

c.f.
SINDRUM-II : BR($\mu^-$ Au $\rightarrow$ e$^-$ Au) < $7 \times 10^{-13}$
SINDRUM-II : BR($\mu^-$ Ti $\rightarrow$ e$^-$ Ti) < $4.3 \times 10^{-12}$
TRIUMF : BR($\mu^-$ Ti $\rightarrow$ e$^-$ Ti) < $4.6 \times 10^{-12}$

**Expected Spectrum of reconstructed momentum for Carbon Target**

- \( \mu\text{-e conv.} \)
- \( \text{DIO} \)

- Decay-In-Orbit 0.015
- After proton < 0.027
  (After proton rate < $10^{-18}$)
- Cosmic-ray induced
  \( e < 0.018 \), \( \mu < 0.001 \)
  (Detector live-time duty = 1/20000)

**Background**

for carbon target ...
- Decay-In-Orbit 0.015
- After proton < 0.027
  (After proton rate < $10^{-18}$)
- Cosmic-ray induced
  \( e < 0.018 \), \( \mu < 0.001 \)
  (Detector live-time duty = 1/20000)
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Summary & Prospects
H Line

Frontend devices in H Line were placed.
Frontend devices in H Line were placed.
H Line

Down Stream Magnets

HB2

HBB1

HS3

H Line

S Line

completed
H Line

- Beamline shield is designed based on Full M.C. simulation of dose using PHITS by N. Kawamura (KEK IMSS).

- Construction of beamline shield will start soon.

current status of the Exp. Hall
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Summary & Prospects
Spectrometer Magnet

- PACMAN Magnet
  - used for PIENU exp. @ TRIUMF, Canada
  - transported from TRIUMF to J-PARC
  - central field = \(0.4 \, T\) (300A) for 105 MeV/c, 70 degree bending
  - Test operation was successfully done in J-PARC MLF.
  - Field measurement was performed.
Spectrometer Magnet

Field calculation by Opera-3d

Comparison between Opera-3d and measured

A field map for momentum analysis was created by Opera-3d based on field measurement.

- tune magnet shape and B-H curve
  ⇒ fit calculation to measured.

PACMAN is ready!
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Detector

Tracking Device

Thin **Multi Wire Proportional Chamber (MWPC)**

2 upstream + 2 downstream of the magnet
= totally 4 chambers

Requirements

- position resolution = **0.3 mm**, thickness = **0.1% X₀** \( \Rightarrow \delta P < 0.5 \text{ MeV/c (RMS)} \)

- tolerate to beam bunch of **10⁸ MIP**

- instantaneous hit rate \( \sim 70 \text{ GHz/mm}² \)

- return to operational **300 nsec** after beam pulse to detect delayed electrons
**Detector**

- **MWPC**
  - 300 mm × 300 mm
  - Wire pitch = 0.7 mm
  - Cathode strip
    - x: 3 mm width
    - y: 15 mm width
  - Flash ADC readout

- **HV Switching**
  - Anode = ~1500 V
  - Switch the voltage for potential wire

- **3 mm cathode strips**
  - 3 mm × 0.7 mm
  - Ar + C2H6 gas

- **~1500 V**
  - Usual
  - Detector protection during the burst, no space charge creation

- **0 V**
  - After prompt burst
  - Delayed signal detection

- **Signal window**
  - ~10 ms
  - Delayed electron signal
  - ~40 ms

- **Voltage**
  - Anode wire voltage
  - Potential wire voltage
  - Time
**Detector**

- **Beam tests**
  - Muon beamline (D-Line) @ MLF, J-PARC
  - Electron Linac @ Research Reactor Institute, Kyoto Univ.

- MWPC Signal
  - disappeared during switching period

- Good performance of HV Switching
  - gain of cathode strip
    ... clear separation between pedestal and signal

- Further analysis is ongoing.

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**All MWPC’s will be ready soon.**

- 2 already available (a little modification)
- 2 assembling

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**Poster Presentation by Natsuki Teshima**

“Development of High-Rate-Tolerant HV-Switching Multi-Wire Proportional Chamber and Its Readout Electronics for DeeMe Experiment”
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After-Proton Background

- After-Proton
  - residual protons in RCS (synchrotron)

- Fast Extraction
  - no After-Proton, in principle

- may be created by beam halo in RCS and extracted to MLF when kicker is off

- induce prompt background in the analysis time window

After-Proton Measurement

- count protons by Beam Loss Monitor (BLM)

\[ f = \frac{\text{After-Proton}}{\text{BLM hits}} = 40 \quad \text{(MC)} \]
After-Proton Background

Beam Loss Monitor
- 3 Scintillators + Pb absorber
- coincidence signal of 3 Scintillators

After-Proton Rate
- total protons extracted = $3.5 \times 10^{20}$ (2 weeks)
- hits in the time window = 3

$\Rightarrow R_{AP} = 3.4 \times 10^{-19}$
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    - **Muon Production Target**
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current muon production target of MLF = graphite (C)

Larger muonic nuclear-capture rate (f_{MC}) is desirable for more sensitive experiment.

τ_{\mu} > 300 \text{nsec} (light Z)

to avoid the prompt background

τ_{\mu} (in silicon) = 0.76 \text{μsec}

f_C: Fraction of the atomic capture of muon to the atom of interest

• single-element material: f_C = 1

• composite material: proportional to Z (Fermi-Teller Z law)

Silicon-Carbide (SiC) → Si : C = 7 : 3
Silicon Carbide Muon Production Target

SiC target ~ 6 times higher physics sensitivity than current carbide target

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Sigma f_c \times f_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite (C)</td>
<td>0.08</td>
</tr>
<tr>
<td>Silicon Carbide (SiC)</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Rotating SiC target

- 10 times strength → 80 times thermal stress
- 8 times larger risk under beam irradiation
- SiC target is under development.
  - increase disk partition and reduce disk radius → lower thermal stress and thermal difference.
  - additional SiC → stop more $\pi$, $\mu$

Prototype of SiC rotating target

beam
DeeMe, $\mu - e$ conversion search at J-PARC MLF

- Sensitivity: $1.2 \times 10^{-13}$ for C target, $2.1 \times 10^{-14}$ for SiC target

A new beamline (H Line) is under construction.

The spectrometer magnet is ready.

- test operation, field magnet, Opera-3d

HV-Switchin MWPC was developed.

- All MWPC’s will be ready soon.

After-Proton measured

SiC muon production target under development

DeeMe will start data taking soon after H Line completed (Japan FY 2016).

(1) Osaka University
(2) UBC
(3) Osaka City University
(4) KEK Accelerator
(5) KEK IMSS
(6) JAEA
(7) KEK IPNS
(8) TRIUMF
(9) Okayama University
(10) PSI
(11) J-PARC Center
Backup
Single Event Sensitivity

(S.E.S)

\[ S = \frac{1}{R_{\pi^-} \times f_{\pi^- \rightarrow \mu^- \text{stop}} \times f_C \times f_{MC} \times A_{\mu-e} \times T} \]

- \( R_{\pi^-} \times f_{\pi^- \rightarrow \mu^- \text{stop}} \) = \mu^- stopping rate per second
- \( f_C \) = atomic capture rate
- \( f_{MC} \) = muon nuclear capture fraction
- \( A_{\mu-e} \) = total acceptance for \( \mu-e \) electrons
- \( T \) = time length of the measurement

- Running time = \( 2 \times 10^7 \) sec (1 year run)

- Background (MC estimated)
  - Decay in Orbit \( 0.09 \)
  - After proton rate (\( R_{AP} \)) < \( 10^{-18} \)
    \( \Rightarrow \) After proton < 0.027 (0.05 90% C.L.)
  - Cosmic induced
    \( e < 0.018 \), \( \mu < 0.001 \)
    \( \Rightarrow \) Detector live-time duty = \( 1/20000 \)
    \( \Rightarrow \) Cosmic ray backgrounds are well suppressed.

- S.E.S estimated by Monte Carlo study

\( 2.1 \times 10^{-14} \) for SiC target

\( 1.2 \times 10^{-13} \) for C target

Current upper limit
\( \text{BR}(\mu^- \text{ Au} \rightarrow e^- \text{ Au}) < 7 \times 10^{-13} \)
(SINDRUM-II)
Source of After Proton

\[
\sum_{1}^{8} \text{KM Kick angle} \approx 17 \text{ mrad}
\]

\textbf{Naive estimation:}
If the rest proton exists and extracts without pulse kicker magnets, a particle needs to have an inclination \((x') \geq 17 \text{ mrad}\)

\(\Rightarrow\) An emittance of \(\approx 2200 \, \pi \text{mm mrad}\)!

\[4 \text{ times of the RCS physical aperture (486 mm mrad)}\] or 7 times of the RCS collimator aperture (324 mm mrad).

First Bunch  Second bunch

Magnetic field by the Kicker

Time structure of extraction beam and after proton

Halo
Beam outer ellipse (H) at the “begin Ext. INS”. (324 ~ 5000 πmm mrad)

We estimated the possible initial conditions that the proton can extract with no kicker excitation. As a result, the protons that has 2500πmm-mrad emittance can partially extract; however, some particles hit the branch chamber.

→ We can catch the existence of after proton by monitoring scintillator signals near this point!
DIO Spectrum Measurement

- Decay In Orbit (DIO) ... major background for μ-e conversion search

  Knowledge about DIO spectrum is very important for background estimation.

- Theoretical model

![Graphs showing DIO spectrum]  
- DIO spectrum calculated by **Czarnecki** (including nuclear recoil)
- without recoil
DIO Spectrum Measurement

- Measurement of DIO spectrum @ 50~70 MeV/c
  
  ![Graphs showing DIO spectrum measurement](image)

  compare with theoretical calculation

- Concept of DIO measurement
  
  similar to momentum calibration ... μ- stopped in the secondary target
  measure the momentum of DIO electron by the spectrometer

- Monte Carlo simulation
  
  - similar way to momentum calibration
  - 10 MeV/c μ- extraction by H-line
  - secondary target = 500μm thickness Graphite foil
  - ~ 4000 DIO electron / day @ 50~70 MeV/c
Subthreshold $\bar{p}$ Production

標的 = $^{12}$C, 5.1° in lab. frame

$p+C \rightarrow \bar{p}+X$

$d^2\sigma/dp \, [\mu b/sr/(GeV/c)]$

$\bar{p}$ angle in lab. frame (degree)

$p$ Momentum [GeV/c]

ビームエネルギー 3 GeV, C標的での各運動量、角度における $\bar{p}$ 生成断面積(first chance collision model)

モデル計算と実験データ

→モデル計算とデータはよくあっている

陽子ビーム

生成標的

$\bar{p}$ 線 $\theta=60°$

Hライン入□

Hライン ... 60° の方向
ビーム入口 ± 14°

→ Hラインへ飛ぶ反陽子は生成されない