Status of the DeeMe Experiment, an Experimental Search for $\mu$-$e$ Conversion at J-PARC MLF

Natsuki TESHIMA
Osaka City University and NITEP

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The DeeMe Experiment


(1) Osaka University (2) UBC (3) KEK (4) JAEA (5) IHEP (6) TRIUMF (7) Osaka City University (8) NITEP (9) Hiroshima University (10) Vietnam National University Ho Chi Minh City (11) University of California, Davis (12) Okayama University
DeeMe Experiment

- Search for charged lepton flavor violating decay
  \[ \mu^- N \rightarrow e^- N \]

This talk
- Charged lepton flavor violation
- Experimental concept
- Current status
- Summary
Charged Lepton Flavor Violation and New Physics

- Charged Lepton Flavor Violation (cLFV)
  - $\mu N \rightarrow eN$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, ...

- Branching ratio for $\mu \rightarrow e\gamma$ suppressed in the Standard Model $< 10^{-54}$
  

- Too low probability to observe

- Some theoretical models beyond the SM predict branching ratios $10^{-13}$ to $10^{-17}$
  - SUSY-GUT, SUSY-seesaw, extended Higgs sector, etc.

- An observation of cLFV processes at large rates means the existence of new physics
What May Happen to Muonic Atoms

**Standard Model**

- Muon decay in orbit (DIO) $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
  
  92% for C, 39% for Al, 33% for Si

- Muon capture (MC) $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$
  
  8% for C, 61% for Al, 66% for Si

**New physics**

- Muon to electron conversion $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

  Charged lepton flavor violation

**Monoenergetic $e^-$**

with $\approx 105$ MeV for C or Al, Si

$$E = m_\mu - B_\mu - E_{\text{rec}}$$

where $B_\mu$: the binding energy of muon

$E_{\text{rec}}$: the nuclear recoil

Muonic atom 1S bound state
Search for cLFV in Photonic and Non-photonic Decays

- Possible processes for cLFV can be classified as Photonic and Non-photonic:
  
  **Photonic**
  \[
  \mathcal{L} = \frac{1}{1 + \kappa} \frac{m_\mu}{\Lambda^2} \mu_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{1 + \kappa} \frac{1}{\Lambda^2} (\mu_L \gamma'^{\mu} e_L) (\bar{q}_L \gamma_\mu q_L)
  \]

  ![Photonic Process Diagram](image)

  Branching ratio for $\mu N \rightarrow e N$
  \[\approx \frac{1}{100}\] of that for $\mu \rightarrow e\gamma$

- It is important to probe the cLFV with as many different approaches as possible.

Original graph by A. de Gouvêa, P. Vogel, Prog. Part. Nucl. Phys. 71, 75-92 (2013)
Sensitivity Goals

**DeeMe**

Aims to achieve

- S. E. S. < $1 \times 10^{-13}$ (C target, 1 year)
- S. E. S. < $2 \times 10^{-14}$ (SiC target, 1 year)

...to observe the CLFV or to improve the current limit by $\times 10$ or $\times 100$

**Current upper limits for $\mu N \rightarrow eN$**

- **TRIUMF**
  - < $4.6 \times 10^{-12}$ (Ti target)

- **SINDRUM-II at PSI**
  - < $4.3 \times 10^{-12}$ (Ti target)
  - < $7 \times 10^{-13}$ (Au target)

**DeeMe**

Aims to achieve

- S. E. S. < $1 \times 10^{-13}$ (C target, 1 year)
- S. E. S. < $2 \times 10^{-14}$ (SiC target, 1 year)

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Places of Experiments

- DeeMe will be conducted at J-PARC Materials and Life Science Experimental Facility MUSE in Tokai Village, Japan
- Takes 1.5 hours by express train from Tokyo
- Pulsed proton beam from 3-GeV RCS
- Fast extraction
- 500 kW → 1 MW (design power)
- 25 Hz double pulses
**Experimental Concept**

- **Target**
- **Pulsed proton beam**

1. $\pi^-$ production
2. $\pi^-$ decay-in-flight into $\mu^-$
3. Muonic atom formation

Secondary beamline H-Line to transport electrons with 105 MeV/c

Magnetic spectrometer

Tracking detectors (four MWPCs)

$\pi^-$ production target = $\pi^-$-decay & $\mu^-$-transport section

$\mu^-$ stopping target in DeeMe experiment

Nucleus

$\mu^- N \rightarrow e^- N$?

$10^{10}$ muonic atoms/sec with RCS 1 MW

$e^-$ with 105 MeV/c

Aug. 29th, 2019 NUFAC2019 at Daegu, Korea
In larger-scale experiments,
- Pion production target
- Pion decay and muon transport section
- Muon stopping target
- Detectors
Backgrounds

- Low-momentum background suppressed by the beamline
- High-momentum tail → need $\Delta p < 0.4\%$ spectrometer
- Beam pion capture $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$, $\gamma \rightarrow e^+ e^-$ at the beam-prompt timing
- Muon Decay in Orbit (DIO) 0.09
- Delayed protons at an irregular timing induce backgrounds < 0.027 (< 0.05 90%CL)
- Cosmic rays suppressed 2 $\mu$s/40 ms $e$: < 0.018, $\mu$: < 0.001
- No antiprotons ($T_p < 3$ GeV)

![Graph showing backgrounds and analysis window]
Status of Beamline, H Line at MLF

- H-line construction is ongoing
- Radiation shield built in 2016
- The spectrometer will be installed in H1 Area
Status of Spectrometer Magnet, PACMAN

- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Shipped to J-PARC in 2014
- Nominal field strength: 0.4 T in the central part for electrons with 105 MeV/c bending 70 degrees
- Operation tested up to 500 A
Status of Detectors

- Four MWPCs & amps. & FADCs & DAQ work well

Four MWPCs manufactured in 2015-2017 are ready

DAQ efficiency $\approx 100\%$

Amplifiers for all channels ready

Publication on the MWPC:

A fast high-voltage switching multiwire proportional chamber

FADCs of real-time lossless compression of waveforms ready

Publication on the FADC:
Detector Requirements

- Expected charged particles to hit the detectors
  - Prompt burst: produced by pulsed proton beams from RCS hitting the target, pass through the H Line
  - Mono-energetic delayed signal electrons: $\mu$-$e$ conversion

- $\approx 70 \text{ GHz/mm}^2$ ($10^6$ to $10^7$ particles/readout) per prompt burst at most

- Need to detect a single electron soon after the prompt bursts

Life time of muonic carbon atoms: 2.0 $\mu$s
Life time of muonic silicon atoms: 0.76 $\mu$s
HV-switching MWPC to Control Gas Gain

- **Number of charged particles**
  - Prompt burst and delayed signal
  - Analysis window

- **Gas gain** $O(1)$ to $O(10^4)$
  - Anode wire
  - Potential wire

- **Wire spacing**
  - 0.7 mm or 0.75 mm

- **Next pulses** 40 ms later
  - 600 ns

- **Dynamic gas-gain control** by HV on the potential wires when $d_{\text{cath-wire}} \gg d_{\text{ano-po}}$

- **Prompt burst and delayed signal**

- **1.5 kV** to **0 V**

- **Stretched alternately**

- **Analysis window**

- **Next pulses** 40 ms later

- **Dynamic gas-gain control**

- **OFF** vs **ON**
Analysis Process

- Output waveform
  - Oscillation caused by HV switching
  - Same shape in every trigger

- Subtract a typical waveform (red) to find hits

- Select four hits and calculate the momentum using GENFIT:
Current Status – Detector Development

- Circuit of amplifiers was slightly modified
- Increase the negative range
- Filling gas was changed
- \( \text{Ar} \) (33%) \( \text{C}_2\text{H}_6 \) (67%), 1650 V applied → \( \text{Ar} \) (80%) iso\( \text{C}_4\text{H}_{10} \) (20%), 1540 V applied

Hit efficiency improving
- \( 90\% \times 90\% \times 80\% \times 80\% \approx 50\% \)
- \( (98\%)^4 \approx 90\% \)
- Further optimization of the gas in progress
Current Status – Measurement of Muon DIO in 2019

- Momentum (45 – 55 MeV/c) of electrons from muon DIO measurement
- D2 Area of D Line
- Mar. 7-13, 2019
- Carbon target
- Tracking eff. improving
- Longer data taking

Mar. 2017 (2 days)
- 1.2×10^6 muon pulses on C, spectrometer set for 55 MeV/c

Jun. 2017 (5 days)
- 6.3×10^5 muon pulses on C, spectrometer set for 55 MeV/c

Measurement of muon beam profile using a plastic-tile scintillator + fiber
Analysis Result of Data in Jun. 2017

- Czarnecki-C calculation agrees well with the measurement (p-val>0.68)
- Detailed analysis in progress

Current Status – Quick Analysis Result of Data in Mar. 2019

**Mode** | **Jun. 2017** | **Mar. 2019** | **Ratio**
--- | --- | --- | ---
Muon DIO ($\mu^-$, 55 MeV/c) | 5028 events (63 runs) | 43769 events (346 runs) | 8.7
Michel edge ($\mu^+$, 52.5 MeV/c) | 23 runs | 35306 events (124 runs) | Tracking eff. improving by 1.6, Longer data taking by 5.4
Acceptance ($\mu^+$, 45 MeV/c) | 16062 events (46 runs) | 86567 events (151 runs) | Tracking eff. improving by 1.6, Longer data taking by 3.3
Summary

- DeeMe to search for $\mu^- \text{N} \rightarrow e^- \text{N}$ with a S. E. S. of $10^{-14}$. Muon production target made of carbon (or silicon carbide).

- The spectrometer is ready.
  - Optimizing filling gas of MWPCs for better performance.

- H-Line construction is in progress.

- Momentum (45-55 MeV/c) measurement of muon DIO from the carbon target. Detailed analysis ongoing.

- Plan to begin data taking for $\mu$-$e$ conversion soon after completing the construction of H Line.
Backup
Measurement of Muonic Atom Yield

- $p_e > 40 \text{ MeV}/c$: Dominated by $e^-$ from $\mu^-$ decay.
- $p_e \sim 50 \text{ MeV}/c$: Michel Edge
- $p_e < 30 \text{ MeV}/c$: Dominated by $e^-$ from $e^+$ scattering where the $e^+$ is coming from $\mu^+$ Michel decay.

- $\rightarrow \mu^-$ stopping rate $= 5 \times 10^9 /\text{sec/MW}$ in a fixed Target, confirmed.
- Good agreement with Geant4/G4Beamline Estimation.
- $10^{10} /\text{sec/MW}$ for SiC Rotating-Target

Will be published!
Measurement of Muon Decay in Orbit Momentum in 2017

Motivation

- To test magnetic spectrometer (4 MWPCs and DAQ) → worked well
- To confirm the medium-momentum region around 55 MeV/c of theoretical calculation by Czarnecki et al.
- At D Line up to $10^6$ muons/s
- Measured the medium-region momentum spectrum of electrons from $\mu^+ \rightarrow e^- \nu_{\mu} \bar{\nu}_e$
- Target: C, Si and SiC
- 2 days in Mar. 2017
- 5 days in Jun. 2017
Analysis of DIO Measurement

- Subtract a template from waveforms
- Sum up sample points in the time and strip direction

Test pulse\(^1\), HV ramp down on potential wires\(^2\), over shoot by PZC circuit\(^3\), detector oscillation\(^4\), HV ramp up on potential wires\(^5\)

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**Graphical Explanation:**

- **One event waveform**
- **Template**
- **Signal**
- **Subtracted waveform**
- **Signal**
- **Event2**
- **Event3**
- **Event4**
- **Event5**

**Analysis Window:**

- 1
- 23
- 4
- 5

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Detector Structure

**MWPC**
- Cathode strip readout
- X-axis readout 3 mm width strip
- Y-axis readout 5×3 mm width strip
- Active area: 250 mm×200 mm

**Readout electronics**
- Amplifiers with large current tolerance
- 10-bit FADCs with a sampling rate of 100 MHz

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