DeeMe
— Yet another experiment to search for muon to electron conversion

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Charged Lepton Flavor Violation

• Charged Lepton Flavor Violation (CLFV)
  - Forbidden in the Standard Model of particle physics.
  - $\mu^- + A \rightarrow e^- + A$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\tau \rightarrow e(\mu)\gamma$, $\tau \rightarrow e(\mu)h$ ...

• Neutron Oscillation may induce the effective CLFV, but it is very small due to the combination of GIM-like mechanism and smallness of the neutrino masses.

$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{e i}^* \frac{m_{\nu i}^2}{M_W^2} \right|^2 \approx 10^{-6} \left( \frac{m_\nu}{10^{-2} \text{eV}} \right)^4$

• CLFV →
  Clear evidence of the physics beyond the Standard Model with neutrino-oscillation extension.
**μ–e Conversion in Nuclear Field**

- **Muon Capture (MC)**
  \[ \mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1) \]

- **Muon Decay in Orbit (DIO)**
  - MC:DIO = 1:1000(H), 2:1(Si), 13:1(Cu)
  - \( \tau(\text{free } \mu^-) = 2.2 \mu s \)
  - \( \tau(\mu^-;\text{Si}) = 0.76 \mu s \)

- **Charged Lepton Flavor Violation (CLFV)**
  \[ \mu^- + (A, Z) \rightarrow e^- + (A, Z) \]

**Clear evidence of the new physics**
\[ \mathcal{L} = \frac{m_\mu}{(\kappa + 1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \frac{\kappa}{(1 + \kappa)\Lambda^2 F}\bar{e}\mu(\bar{q}q + \bar{e}e) \]

\[ [\mu^- + A \rightarrow e^- + A] \text{ vs. } [\mu^+ \rightarrow e^+ + \gamma] \]

- SUSY-GUT, SUSY-seesaw
- Higgs mediated processes
- Doubly Charged Higgs Boson (LRS etc.)
- Little Higgs Models
- Randall-Sundrum Models
- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Multi-Higgs Models

graph showing photonic and non-photonic categories with different models and constraints.
Principle of Measurement

- Process: $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed: $\sim 1\mu S$
  - No accidental backgrounds
  - Physics backgrounds
    - Muon Decay in Orbit (DIO)
      - $E_e > 102.5$ MeV (BR: $10^{-14}$)
      - $E_e > 103.5$ MeV (BR: $10^{-16}$)
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      - $\gamma \rightarrow e^+ e^-$
    - Prompt timing

Recent Upper Limits
- 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: $BR[\mu^- + Ti \rightarrow e^- + Ti] < 4.6 \times 10^{-12}$
Light-weight $\mu$-e Conversion Exp.?  
MELC, MECO, COMET, Mu2e

- $\mu$-e conversion electron may directly come from the production target.
- Analogy to the surface muon.
Measurement of Muonic Atom Yield @ 2009

- $p_e > 40$ MeV/c: Dominated by $e^-$ from $\mu^-$ decay.
- $p_e \sim 50$ MeV/c: Michel Edge
- $p_e < 30$ MeV/c: Dominated by $e^-$ from $e^+$ scattering where the $e^+$ is coming from $\mu^+$ Michel decay.
- $\to \mu^-$ stopping rate = $5\sim6 \times 10^9$ /sec/MW in a 1st fixed Target.
- Good agreement with Geant4/G4Beamline.
- $10^{10}$/sec/MW for SiC Rotating-Target
DeeMe

• Process: $\mu^{-}+(A,Z) \rightarrow e^{-}+(A,Z)$
  – A single mono-energetic electron
    • 105 MeV
    • Delayed: $\sim 1\mu S$
  • No accidental backgrounds
  • Physics backgrounds
    – Muon Decay in Orbit (DIO)
      • $E_e > 102.5$ MeV (BR: $10^{-14}$)
      • $E_e > 103.5$ MeV (BR: $10^{-16}$)
    – Beam Pion Capture
      • $\pi^{-}+(A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma+(A,Z-1)$
      • Prompt timing
        • Low Energy main part: suppressed by the beamline.
        • High Energy tail: Magnet Spectrometer ($\Delta p < 0.5\%$)
        • Main pulse burst: State-of-the-art MWPC that becomes operational quickly after a burst.
        • Delayed-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{DP}<10^{-17}$. 
J-PARC MLF

- **LINAC**
  - H⁺, 400 MeV, 50 mA
  - 50 Hz

- **RCS**
  - 3 GeV, 333 μA, 1MW: High Power
  - 25 Hz, Fast Extraction: High Purity
  - Material and Life-science Facility (MLF)

- **MR**
  - 30 GeV, 15 μA
  - Fast and Slow EX

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MUSE: IMSS/Muon Facility
Earthquake

300 kW

Accident at Hadron Facility

as of December 21, 2016

• ~10 months interruption due to the earthquake

• ~1 month interruption due to the fire in MLF

• Interruption due to troubles of Hg-target

Startup of the user program in Dec. 2008

1 MW eq. pulse

DeeMe Collaboration

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DeeMe Project

- High-Power High-Purity Pulsed Proton from J-PARC RCS
- Start with Graphite Target
  - Aiming to upgrade to a SiC Target
- Large-Acceptance Beam line (H-Line)
- State-of-the-Art HV-Switching MWPC
- Single Event Sensitivity
  - $1 \times 10^{-13}$ (Graphite, $2 \times 10^7$ sec)
  - $2 \times 10^{-14}$ (SiC), $5 \times 10^{-15}$ ($8 \times 10^7$ sec)
- Proposed to KEK/IMSS in 2010
- Stage-2 Approved from Muon PAC IMSS
- Grant-in-Aid for detector construction
  - completed
- H-Line under construction
  - upstream-half completed
  - beamline shield completed
  - downstream at 2018 summer
- Aiming to start in 2018.
Sensitivity and Backgrounds

• Signal Sensitivity (SiC)
  – S.E.S.: $2 \times 10^{-14}$ (1 MW, $2 \times 10^7$ sec)

• Backgrounds
  – $R_{AP} < 10^{-18}$
  – Detector live-time Duty = 1/20000
    that suppresses cosmic-ray BG
  – no anti-protons ($E_p = 3$ GeV $< 5.6$ GeV)

<table>
<thead>
<tr>
<th>Background</th>
<th>Value (90%CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIO BG</td>
<td>0.09</td>
</tr>
<tr>
<td>Delayed-Proton BG</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>Cosmic-Muon Induced</td>
<td>&lt;0.018</td>
</tr>
<tr>
<td>Cosmic-Muon Induced Muon</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Radiative Muon Capture BG</td>
<td>&lt;0.0009</td>
</tr>
</tbody>
</table>

• If we could extend the running-time up to $8 \times 10^7$ sec
  – Standard Cut: S.E.S. = $0.5 \times 10^{-14}$ ($N_{BG} < 0.64$)
  – Tighter Cut: S.E.S. = $0.6 \times 10^{-14}$ ($N_{BG} < 0.17$)
    $N_{BG}$ could be much less with improved BLM system.
In-situ Monitoring of Backgrounds

• Momentum Domain
  – Moderate $\Delta p$ of H-line makes it possible to monitor backgrounds in-situ:
    • DIO ($p < 102.5$ MeV/c)
    • Beam Backgrounds ($p > 105.6$ MeV/c)
  – Number-of-muon Calibration by using DIO.

• Time Domain
  – Monitor Off-Timing Protons
    • Beam-Loss Monitor @ RCS
    • Spectrometer Activities
  – Cosmic-Ray Background
    • Duty-factor $1/20000$
Delayed-Protons from RCS

- RCS has a very large aperture (to reduce the beam loss).
  - Vacuum Duct = 486\pi \text{ mm.mrad} \quad \text{(Collimator: 350}\pi \text{ mm.mrad)}
  - Transport to MLF = 324\pi \text{ mm.mrad}
  - Kick Angle = 17 \text{ mrad} \rightarrow 2000\pi \text{ mm.mrad}
- Fast Extraction --- No residual protons in a ring.
- High-Purity High-Power Pulsed Proton Beam

\[ R_{DP} < 8 \times 10^{-19} \quad \Leftrightarrow \quad N_{DP} < 0.04 \]
Beamline: H-line

- Concept: Jaap Doornbos (TRIUMF)
  - Leader: Naritoshi Kawamura (KEK)
  - Multiple purpose: DeeMe + g-2 + muon-HFS
  - Large Acceptance: > 110 msr
  - Large Momentum Acceptance: BG monitor
    - DIO backgrounds (p < 102.5 MeV/c)
    - Prompt backgrounds (p > 105.0 MeV/c)
- Upstream; already installed in the summer of 2012.
- Downstream; Engineering Design finished;
  - radiation shielding Installation completed;
  - is going to be installed in 2018 summer.
H-line: Construction of Radiation Shields @ 2016 summer
Spectrometer

• Orthodox Dipole Spectrometer
  – $\Delta p < 0.5$ MeV/c
  – **A magnet from TRIUMF**

• Prompt Burst: $\sim 10^8$/200-ns
  – Need to reduce the drop of gas-gain coming from space-charge effect of ions.
Potential-Wire Voltage Switching MWPC

Anode wire: 1150V
Potential wire: 0V
Expected gas gain: $\sim 10^4$

Anode wire: 1150V
Potential wire: 1000V
Expected gas gain: $\sim 7$

Cathode Plane (0V)
Anode Wire (1150V)
Potential Wire
Electric field contour
Cathode Plane

Electric field Profile

JPS Meeting 28/March/2014 @ Tokai University Shonan Campus

PTEP 2017 (2017) 023C01: https://doi.org/10.1093/ptep/ptw193
MWPC Development

Prototype 1 @2012

Prototype 2 @2014

Preamps @ 2015

Production @ 2015

Raw Waveform

Baseline-subtracted Waveform

Prompt Burst
A single-stage PZC right after the 1st transistor to cancel 1/t tail that comes from slow ion movement.
Lowe-cost FADC

- Originally developed for J-PARC/E36 by Y. Igarashi
- Firmware completely replaced by N.M.Truong
- Lossless data reduction
- $70 / channel.
Beam Tests

Now, it is stable and operational w/o any breakdowns. Confirmed a good gas gain.
Summary

• There is a competitive merit of physics in searching for μ-e conversion at sensitivity of $10^{-14}$ in timely manner.

• It is important to maximize the potential of major discovery at J-PARC.

• DeeMe, yet another mu-e conversion search with totally different method from COMET and Mu2e, creates harmonious diversity for J-PARC.

• DeeMe has already acquired **Stage-2 Approval from muon-PAC of KEK/IMSS**.

• Construction of detector system has completed with Grant-in-Aid for Scientific Research of Japan (Basic Science S, 2012–2016).

• It is necessary to build a large-acceptance beamline (H-line). The H-line can be used for other experiments, such as g-2.

• We can start the physics measurement with a Graphite target. The development of SiC target will be continued and installed in timely manner for the ultimate sensitivity.

• We are hoping to start soon after the completion of the beamline construction (current estimate: 2018). No beam-time conflicts with T2K, KOTO or whatever the physics programs with the main ring of J-PARC.
End of Slides