Muon g-2/EDM experiment at J-PARC

15th Tau workshop
Sep 27, 2018
Tsutomu Mibe (KEK)
for the J-PARC g-2/EDM collaboration
www.g-2.kek.jp
International school on muon dipole moment and hadronic effects

Sep 17-21, 2018 @BINP

https://indico.inp.nsk.su/event/14/
Features:

- Low emittance muon beam (1/1000)
- No strong focusing (1/1000) & good injection eff. (x10)
- Compact storage ring (1/20)
- Tracking detector with large acceptance
- Completely different from BNL/FNAL method
The Collaboration

99 “current” members from 41 institutions, 7 countries.
muon g-2 and EDM measurements

In uniform magnetic field, muon spin rotates ahead of momentum due to $g-2 \neq 0$

general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

BNL E821 approach
$\gamma = 30$ (P=3 GeV/c)

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

FNAL E989

J-PARC approach
$E = 0$ at any $\gamma$

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} \right) \right]$$

J-PARC E34
Conventional muon beam (BNL, Fermilab)

proton → π⁺ → µ⁺

emittance ~1000π mm mrad

Strong focusing
Muon loss
BG π contamination
Muon beam at J-PARC

proton → π⁺ → μ⁺

- pion production
- decay

emittance
~1000π mm • mrad

Strong focusing
Muon loss
BG π contamination

Reaccelerated thermal muon

emittance
1π mm • mrad

Free from any of these
Re-accelerated thermal muon

<table>
<thead>
<tr>
<th></th>
<th>surface muon</th>
<th>thermal muon</th>
<th>accelerated muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>3.4 MeV</td>
<td>30 meV</td>
<td>212 MeV</td>
</tr>
<tr>
<td>$p$</td>
<td>27 MeV/c</td>
<td>2.3 keV/c</td>
<td>300 MeV/c</td>
</tr>
<tr>
<td>$\Delta p/p$</td>
<td>0.05</td>
<td>0.4</td>
<td>$4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Experimental sequence

Surface muon beam (28 MeV/c)

Thermal muonium (3 keV/c)

Ultra-slow muon (3 keV/c)

Acceleration + injection (300 MeV/c)

Storage and detection (300 MeV/c)

μ⁺ → e⁺
Expected time spectrum of $e^+$ in $\mu \rightarrow e^+ \nu \nu$ decay

$$\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} (\vec{\beta} \times \vec{B}) \right]$$
## Expected uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of muons in the storage magnet</td>
<td>$5.2 \times 10^{12}$</td>
</tr>
<tr>
<td>Total number of positrons</td>
<td>$0.57 \times 10^{12}$</td>
</tr>
<tr>
<td>Effective analyzing power</td>
<td>0.42</td>
</tr>
<tr>
<td>Statistical uncertainty on $\omega_a$ [ppb]</td>
<td>450</td>
</tr>
<tr>
<td>Statistical uncertainty on $\omega_p$ [ppb]</td>
<td>100</td>
</tr>
<tr>
<td>Uncertainties on $a_\mu$ [ppb]</td>
<td>$460$ (stat.)</td>
</tr>
<tr>
<td></td>
<td>$&lt; 70$ (syst.)</td>
</tr>
<tr>
<td>Uncertainties on EDM [$10^{-21}$ e⋅cm]</td>
<td>1.4 (stat.)</td>
</tr>
<tr>
<td></td>
<td>0.36 (syst.)</td>
</tr>
</tbody>
</table>
J-PARC Facility (KEK/JAEEA)

Neutrino Beam To Kamioka

Material and Life Science Facility

Main Ring (30 GeV)

LINAC

3 GeV Synchrotron

Hadron Hall

Bird’s eye photo in Feb. 2008
Proposed experimental site
Material and Life science Facility in J-PARC

- Muon production target
- MuSEUM
- DeeMe
- Muon linac
- Parking lot
- H-Line
- g-2/EDM storage magnet
- New Electric Power substation
- Separation neutron source
H-line being constructed!

Photo by T. Yamazaki

To g-2/EDM
H-line being constructed!

Photo by T. Yamazaki
New power station being constructed

Photo by T. Yamazaki
Production target (20 mm)

3 GeV proton beam (333 uA)

Surface muon beam (28 MeV/c)

Muonium Production
(300 K ~ 25 meV → 2.3 keV/c)

Silicon Tracker

66 cm

Super Precision Storage Magnet (3T, ~1 ppm local precision)

Resonant Laser Ionization of Muonium (~10⁶ µ⁺/s)

Δ(g-2) = 0.1 ppm

ΔEDM = 10⁻²¹ e·cm
Muonium ($\mu^+e^-$)

Silica aerogel ($\text{SiO}_2, 30\text{ mg/cc}$)

Laser-ablated holes

P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
Muon LINAC

<table>
<thead>
<tr>
<th>Component</th>
<th>Length</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ</td>
<td>3.2 m</td>
<td>324 MHz</td>
</tr>
<tr>
<td>IH-DTL</td>
<td>1.4 m</td>
<td></td>
</tr>
<tr>
<td>DAW</td>
<td>16 m</td>
<td>1296 MHz</td>
</tr>
<tr>
<td>DLS</td>
<td>10 m</td>
<td></td>
</tr>
</tbody>
</table>

Phase space distributions after muon LINAC (simulation)
Muon RF acceleration for the first time!

J-PARC MLF D2 area, October 2017

Slide by M. Otani
Muon RF acceleration for the first time!

J-PARC MLF D2 area, October 2017

$\mu^+$ (~4 MeV)

5.6 keV

90 keV


Slide by M. Otani
An accelerating structure (IH-DTL cavity) to 1.3 MeV

Muon beam injection and storage

Horizontal injection + kicker
(BNL E821, FNAL E989)

3D spiral injection + kicker
(J-PARC E34)

Injection efficiency: 3-5\%(*)

Injection efficiency: \sim 85\%

(*) PRD73,072003 (2006)

Muon storage magnet and detector

Drawn by Hitachi Co.

Muon storage orbit

Cryogenics

Iron yoke

Superconducting coils

666 mm

2900 mm

e+ tracking detector

M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)
Positron tracking detector

• Requirements
  – Detection of e+ (100<E<300 MeV)
  – Reconstruction of momentum vector
  – Stability over rate changes (1.4 MHz → 14 kHz)

• Specifications
  – Sensor: p-on-n single-sided strip
  – Number of vanes: 40
  – Number of sensors: 640
  – Number of strips: 655,360
  – Area of sensors: 6.24 m²
First test module tested with muon at J-PARC
8. DETECTOR AND RECONSTRUCTION

Detector acceptance and reconstruction efficiency

Yamanaka + Sato

Simulation

Accepted x Efficiency

- 0.06 tracks/ns
- 0.6 tracks/ns
- 6 tracks/ns

used for g-2 analysis

Responses to recommendations given by the focused review committee, Dec. 2017

Yamanaka + Sato

Acceptance x Efficiency

Detector acceptance and reconstruction efficiency

Yamanaka + Sato

Simulation

Acceptance x Efficiency

- 0.06 tracks/ns
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Responses to recommendations given by the focused review committee, Dec. 2017

Yamanaka + Sato
B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC
Field shimming by iron arrays

Before shimming

B(μT)

azimuthal angle (rad)

axial position (mm)

-250 -200 -150 -100 -50 0 50 100 150 200 250 -2 -1 0 1 2

r = 140 mm

After shimming

B(μT)

azimuthal angle (rad)

axial position (mm)

-250 -200 -150 -100 -50 0 50 100 150 200 250 -2 -1 0 1 2

Plots by K. Sasaki

Measured by single probe system

Spheroid : r=100 mm, z=300 mm

860 ppm p-p in 50 cm DSV

Field shimming by iron arrays

After shimming #3

2015/05/19

860 ppm

-600 ppm

400 ppm

0.4 ppm

-0.5 ppm
Cross calibration of B-field probes
0. Executive Summary

The focused review committee has reviewed the updated TDR and collaboration responses to our recommendations. While there is substantial work ahead to successfully deliver all of the necessary development and studies to assure success of the experiment, the committee believes that the E34 collaboration has made significant progress and is well positioned to address remaining issues and therefore unanimously recommends that E34 proceed to Stage-2.
Summary

• The J-PARC muon g-2/EDM experiment will measure g-2 and EDM with completely different method.

• Features:
  • Low emittance muon beam (1/1000)
  • No strong focusing (1/1000)
  • Good injection eff. (x10)
  • Compact storage ring (1/20)
  • Tracking detector with large acceptance
  • Completely different from BNL/FNAL method

• We are moving to R&D to construction phase.
• In coming years,
  – Construction of muon beamline (H-line)
  – Demonstration of “muon cooling”
  – Re-acceleration to 1 MeV