Muon g-2/EDM Measurement at J-PARC

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10th International Workshop on Fundamental Physics Using Atoms
January 8, 2018
Muon g-2 and EDM

- Anomalous magnetic moment
  \[ a_\mu = \frac{g - 2}{2} \]
  - Calculated at the order of 0.4 ppm precision in the SM for muon
  - The best experimental uncertainty is 0.54 ppm by BNL E821.
  - There is ~3 \( \sigma \) deviation between the theory and the experiment.
  - New physics (e.g. SUSY) can explain this discrepancy.

- Electric dipole moment (EDM)
  - If non-zero EDM exists, it indicates CP violation.
  - Current experimental limit is at \(<10^{-19} \text{ e\cdot cm}\) by BNL E821.
  - The SM expectation of muon EDM is \(~2 \times 10^{-38} \text{ e\cdot cm}\).
  - New physics (e.g. SUSY) predict much larger EDM.
Muon Spin Precession Vector

- The $g$-2 and EDM are obtained by measuring spin precession vector
  \[
  \vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right] + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)
  \]

- In the previous experiments by CERN and BNL and ongoing experiment by FNAL $\to$ magic momentum: $p=3.094$ GeV/c
  \[
  \vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right] + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)
  \]

- In J-PARC E34 experiment $\to$ $E=0$
  \[
  \vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \vec{\beta} \times \vec{B} \right]
  \]
J-PARC Experiment Overview

Δ(μ) ≈ 0.1 ppm
EDM ≈ 10^{-21} e·cm

Features:
• Super-low emittance muon beam
• No strong focusing
• Compact storage ring
• Full tracking detector
• Completely different from BNL/FNAL method

3 GeV proton beam
(333 uA)

Production target
(20 mm)

Surface muon beam
(28 MeV/c)

Muonium production
(300 K ~ 25 meV ⇒ 2.3 keV/c)

Super precision storage magnet
(3 T, ~1 ppm local precision)

Silicon Tracker

Δ(μ) ≈ 0.1 ppm
EDM ≈ 10^{-21} e·cm

Features:
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• No strong focusing
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• Full tracking detector
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J-PARC Facility

- LINAC 400 MeV
- Rapid Cycle Synchrotron 3 GeV
- Neutrino Beam to Kamioka
- Main Ring 30 GeV
- Hadron Hall
- Material and Life Science Facility
For high intensity beam and long beam time, a dedicated beam line will be constructed.
H-line Construction Status

- Frontend devices and radiation shield were already installed by JFY2016.
- Construction of the new power sub-station for H-line has been started.
  - Bedding of the station and renovation of MLF wall were done.
Muon Source

- Muonium yield was measured for various aerogel samples and long term stability was tested in beam test at TRIUMF in 2017.
- Laser system is constructed in U-line and achieved 10 μJ.
  - Development for >100 μJ is ongoing.
• Basic design for all structures was finished.

• Next goal was demonstration of muon acceleration.
  – Electro-static acceleration was already demonstrated.
  – Test of muon acceleration using RFQ has been performed.
Muon Acceleration Beam Test

μ⁺ (~4 MeV)

Oct. 24-30@J-PARC MLF D2

Mu production

RFQ

5.6 keV

90 keV

Diagnostic line (Quadrupole pair and bending)

Detector
The first muon (Mu⁻) RF linear acceleration in the world!

- Paper draft is in preparation.
Spiral Injection

• Accelerated muon beam is injected to storage region vertically using spiral injection.
  – High injection efficiency > 80%

• Spiral injection is being tested using electron beam.

CCD image of electron beam trajectory
Storage Magnet

- 3 T MRI-type solenoid magnet will be used.
  - Weak focusing magnetic field is also applied to keep beam size.
  - Several designs are made and their performances are being evaluated in simulation.
- Field uniformity is achieved by shimming.
  - Local uniformity of 1 ppm is confirmed with the magnet used in MuSEUM experiment.
  - NMR probe will be used for field measured. The probe was cross-calibrated at ANL.

Magnetic field after shimming
Positron Tracking Detector

- Tracking detector consists of 48 vanes and each vane has 8+8 silicon strip sensors.
  - Detail of structure design is on-going as well as construction procedures.
- Track reconstruction algorithm is being developed.
  - With the current version of algorithm, more than 90% efficiency is expected even in the highest pileup condition.
Detector Module

- The detector module consisting of one silicon strip sensor and prototype of readout ASIC was already put into MuSEUM experiment and recorded physics data.
  - The next version of detector module will be more close to the final version and will be put into the beam time of MuSEUM experiment in autumn of this year.

**Silicon strip sensor**
- Mass production has been started.

**Specification**
- $98.77 \times 98.77$ mm
- 190 μm pitch
- 512ch $\times$ 2 block

**Readout boards**
- Final prototype readout-ASIC is being fabricated.

**Specification**
- 4 MIP range
- 839 e$^{-}$ ENC
- 128 ch/chip
- 8096 buffer
- 5 ns sampling
Measurement of $a_\mu$

- $a_\mu$ is calculated from
  $$a_\mu = \frac{R}{\lambda - R}$$

  $\lambda = \mu_\mu / \mu_p$
  Muon/proton magnetic moment ratio
  - will be measured in MuSEUM experiment in 0.01 ppm

  $R = \omega_a / \omega_p$
  Muon anomalous spin precession frequency/Larmor frequency of proton
  - will be measured in this experiment
    - Several error sources are not yet fully evaluated but they are expected to be constrained less than 0.1 ppm on $a_\mu$.

### Systematic uncertainties on $\omega_a$

<table>
<thead>
<tr>
<th>Source of errors</th>
<th>Error on $\omega_a$ [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing shift due to pileup</td>
<td>&lt; 36</td>
</tr>
<tr>
<td>Pitch correction</td>
<td>13</td>
</tr>
<tr>
<td>$E$-field</td>
<td>10</td>
</tr>
<tr>
<td>High energy positron</td>
<td>TBD</td>
</tr>
</tbody>
</table>

### Systematic uncertainties on $\omega_p$

<table>
<thead>
<tr>
<th>Source of errors</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute calibration standard probe</td>
<td>25 ppb</td>
</tr>
<tr>
<td>Calibration of trolley probe</td>
<td>20 ppb</td>
</tr>
<tr>
<td>Total magnetic field $B_{tot} = B_{main} + B_{weak}$</td>
<td>45 ppb +TBD</td>
</tr>
<tr>
<td>Uncertainty from the muon distribution</td>
<td>TBD</td>
</tr>
<tr>
<td>Field decay</td>
<td>&lt; 10 ppb</td>
</tr>
<tr>
<td>Eddy current from kicker</td>
<td>0.1 ppb</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
</tr>
</tbody>
</table>
Measurement of EDM

- EDM is obtained by fitting up-down asymmetry of the number of positrons.
  \[ A_{UD} = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = \frac{A_{EDM} \sin(\omega t + \phi)}{1 + A \cos(\omega t + \phi)} \]

- Dominant systematic uncertainty comes from detector misalignment.
  - Skew is the most demanding alignment and <10 µrad is required for EDM < 10^{-21} e\cdot cm.
  - Detector alignment will be performed with laser interferometer system and positron tracks.

**Systematic uncertainties on EDM**

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>EDM 10^{-21} [e\cdot cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector misalignment</td>
<td>0.36</td>
</tr>
<tr>
<td>Axial E field</td>
<td>0.001</td>
</tr>
<tr>
<td>Radial B field</td>
<td>0.000001</td>
</tr>
<tr>
<td>Total</td>
<td>0.36</td>
</tr>
</tbody>
</table>
• Revised version of technical design report has been submitted to review committee on December 15, 2017.
  – Updated to reply Focused Review Committee’s recommendations
• J-PARC PAC meeting will be held on January 15-17, 2018 and E34 experiment will receive the review.
E34 Collaboration

- Authors has been increased from 144 to 158 in the last year.
- Group structure is organized.
Summary

• In J-PARC E34 experiment, measurement of muon g-2 and EDM are planned with a different method from the previous experiments.

• Developments of each component of the experiment are ongoing and there are several achievements in the last year.

• To proceed to the next approval stage, the collaboration will receive the review soon.