J-PARC muon g-2/EDM experiment

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On behalf of the J-PARC muon g-2/EDM collaboration
Muon anomalous magnetic moment \((a_\mu, g-2)\)

- Deviation of \(g\)-factor from the prediction of Dirac equation for fermions.

\[
- a_\mu = \frac{g-2}{2} = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(\text{New Physics})
\]

- 4.2\(\sigma\) deviation between the SM prediction and measurements
  - \(\sigma_{\text{SM}} : 0.37\) ppm [white paper]
  - \(\sigma_{\text{exp}} : 0.35\) ppm [BNL+FNAL]

Electric Dipole Moment (EDM)

- If non-zero EDM exists, it means T-violation. \(\Rightarrow \) CP-violation
- Exp. upper. limit : \(d < 1.8 \times 10^{-19} e \cdot \text{cm}(95\% \text{ C.L.})\) by BNL E821.

\(\Rightarrow \) A new experiment to measure muon g-2 and EDM at J-PARC
**Experimental Approaches**

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

\[ \bar{\omega} = \bar{\omega}_a + \bar{\omega}_\eta \]

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

- $g$-2 term
- EDM term

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**J-PARC E34 Simulation**

- $P_\mu = 50\%$  $N_\mu = 5.7 \times 10^{11}$
- $200 \text{ MeV} < E_\mu < 275 \text{ MeV}$

- $d_\mu = 1 \times 10^{-20} \text{ e cm}$

- Up-down asymmetry

- $\propto$ EDM
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**BNL E821 & FNAL E989**
- Magic momentum
  \[ \gamma = 29.3 \quad (p = 3.1 \text{ GeV}/c) \]
- Weak electric focusing.

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**J-PARC E34**

- No electric field
- Very weak magnetic focusing

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

→ Different systematic uncertainty.
→ Clear separation of $\vec{\omega}_a$ and $\vec{\omega}_\eta$. 
Reaccelerated thermal muon beam

- No requirement of strong beam focusing by an electric field
  - Weak focusing $B$-field.
- Free from magic momentum of 3.094 GeV/c
  - Lower momentum beam of 300 MeV/c
    - Compact storage ring with excellent uniformity ($\Delta \sim 0.1$ ppm)
    - Full tracking detector for decay positron

Conventional muon beam
Emittance $\sim 1000 \pi$ mm $\cdot$ mrad
- Strong focusing with electric field
- Muon loss
- Pion background

Reaccelerated thermal muon beam
Emittance $\sim 1 \pi$ mm $\cdot$ mrad
- Free from any of the above
J-PARC muon g-2/EDM Experiment

1. Muon Beam Line and experimental area
2. Thermal muon
3. Muon linac
4. Injection
5. Storage
6. Detector

- Surface $\mu^+$
- Cooling (25 meV)
- Acceleration (210 MeV)
- Injection
- Storage
- Positron detector

Initial goal          Final goal
$g-2 \sim 0.45 \text{ ppm}$  \rightarrow 0.1 \text{ ppm}
$\text{EDM} \sim 10^{-21} \text{ e } \cdot \text{ cm}$
Construction of H-line up to H1 area has been finished.

The first beam of H-line was detected on Jan. 15, 2022.
The extension building (H2) is being ready for construction.
- **Surface muon (27 MeV/c) is stopped at a target and muonium ($\mu^+e^-$) is emitted.**

- A muonium is ionized by laser and thermal muon beam (25 meV/c) is produced.

**Muonium production target: Laser ablated Silica aerogel**

- ×10 more muonium emission rate compared to flat silica aerogel.
- Various laser-ablated structures and aerogel materials were studied.
Surface muon (27 MeV/c) is stopped at an target and muonium (μ⁺e⁻) is emitted.

A muonium is ionized by laser and thermal muon beam (25 meV/c) is produced.

Laser-resonant ionization methods

Original plan: an intense 122 nm (Lyman-α) laser
  - Efficient single photon excitation
  - Challenging 100 μJ Lyman-α laser development

Plan B: ionization scheme with 244 nm laser
  - Established laser technology
  - Collaboration with the muonium 1S-2S spectroscopy measurement experiment
Muon Acceleration

- Thermal muons are reaccelerated up to 300 MeV/c by muon LINAC.
  - Fast acceleration to avoid muon decay loss
  - No emittance growth.
- Different cavity to realize fast re-acceleration through wide β region.
- **World’s 1st acceleration of μ in Mu*( = μ⁺e⁻e⁻) in 2018 by RFQ**
  - Acceleration of thermal μ is planned in 2023 by RFQ
The rest of acceleration cavities are designed and their performances are being evaluated with prototypes.

- IH-DTL: Fabrication of real-type was completed.
- DAW-CCL: 1st tank is being fabricated.
- DLS: Prototypes will be fabricated FY2022

R&Ds for beam monitor system is also ongoing.

For injection of muon beam into compact storage ring, the 3D-spiral injection scheme has been invented.

- Smooth connection between injection and storage regions.
- Pulsed magnetic kicker to guide muon beam into stable orbit.
- Weak-focusing magnetic field to control muon beam within a few cm.

Higher injection efficiency: ~85% ⇒ 3-5% @BNL E821 [PRD 73 072003 (2006)]
Demonstration experiment of the injection scheme with low momentum electron beam is progressing well.
- Visualize 3D spiral beam trajectory with CCD camera.
- Prototypes of kicker was fabricated and will be demonstrated.

Demonstration experiment setup

Prototypes of kicker
• 3T MRI-type superconducting solenoid magnet is used to store a muon beam.

M. Abe et al., Nuclear Inst. and Methods in Physics Research A890, 51 (2018)
Muon Storage Magnet

- High uniformity of the magnetic field is achieved by **shimming**.
  - Local uniformity of 1 ppm was confirmed with the magnet used in the MuSEUM experiment.
- **High precision NMR probes** are used for field measurement.
  - Cross-calibration is underway in a joint research project between Japan and the US.
  - An accuracy of 15 ppb has been achieved.

Cross-calibration of FNAL and J-PARC field probes
Positron tracks are measured by **Silicon-strip detector**.

- Positrons with a momentum of 100-300 MeV/c
- High hit rate capability (6 tracks/ns) and stability over early to late rate changes (1.4 MHz → 10 kHz)
- Design optimized for pulsed beam.

**Event display with 25 muons**

**Quarter vane module**

**Reconstruction efficiency**

**Simulation**

- 66 cm
- 4 sensors
- 32 ASICs
- 0.06 tracks/ns
- 0.6 tracks/ns
- 6 tracks/ns

used for g-2 analysis
Major components are in or completed the mass-productions.
Prototype module is being assembled.

**Flexible printed circuit boards**
- Made by Fujikura Ltd.
- Mass-production: done

**Silicon-strip sensor**
- Made by Hamamatsu Photonics K.K., S13804
- Strip pitch: 190 μm
- Mass-production: ongoing

**Quarter vane module**

**Readout ASIC (SiT)**
- Silterra 180-nm CMOS process
- Binary output with sampling interval of 5 ns
- Mass-production: done

**Rigid printed circuit boards**
- Prototypes were fabricated and being tested.
Statistics Estimation

- Overall efficiency: $1.3 \times 10^{-5}$
- Assuming $2.2 \times 10^7$ sec (~255 days) of data taking, total number of reconstructed $e^+$ is $5.7 \times 10^{11}$.

- 2-year running will reach the BNL precision of $a_\mu$.
- Systematic uncertainties will be much smaller than the statistical ones.
Reach the BNL precision in ~2-year running.
J-PARC Muon g-2/EDM Collaboration

110 members from Canada, China, Czech, France, India, Japan, Korea, Netherlands, Russia, USA

Subgroups
- Surface muon beam
  leader: T. Yamazaki, N. Kawamura
- Ultra-slow muon
  leader: K. Ishida, G. Marshall
- LINAC
  leader: Y. Kondo, M. Otani
- Injection and storage
  leader: H. Iinuma
- Storage magnet, field measurements
- Detector
  leader: T. Yoshioka
- DAQ and computing
  leader: Y. Sato, K. Hayasaka
- Analysis
  leader: T. Yamanaka

Interface coordinators
- K. Ishida
- M. Otani
- Y. Kondo
- H. Iinuma
- T. Kume
- Y. Sato
- T. Suehara
- T. Yamanaka

Committees
- Speakers committee
  chair: K. Ishida
- Publication committee
  chair: B. Shwartz

New Domestic institutes:
- Welcome University of Groningen
- Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.
- KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

The 24th J-PARC muon g-2/EDM collaboration meeting, June 8-10, 2022
J-PARC muon g-2/EDM experiment aims to measure muon g-2 and EDM with a method different from BNL/FNAL experiment.
- Low emittance muon beam with no strong focusing.
- MRI-type storage ring with a good injection efficiency and high uniformity of local B-field.
- Full-tracking detector with large acceptance

The experiment is getting ready for realization.
- Construction of new muon beam line “H-line”
- R&Ds of the subsystem is going well.

Expecting data taking from FY2027.