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Muon $g-2$/EDM Experiment at J-PARC

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The anomalous magnetic moment of muon can be calculated in the Standard Model (SM) taking into account the quantum electrodynamics (QED), electroweak, and hadronic contributions, however, the current experimental results show a discrepancy with the theoretical expectation by more than 3σ. This may imply a presence of the New Physics, therefore, precision measurements of the muon anomaly is crucial. The latest experimental results were obtained by E821 at the Brookhaven National Laboratory (BNL) with an uncertainty of 0.54 ppm, and its successor, Muon $g-2$ Experiment at the Fermi National Accelerator Laboratory (FNAL) is in operation to reduce the uncertainty. At the Japan Proton Accelerator Research Complex (J-PARC), another experiment for the precision measurement of the muon anomaly as well as the electric dipole moment of muon is being developed using a new experimental approach. Instead of using a storage ring with a magic momentum of muon as E821 and FNAL, a storage magnet with a three-dimensional injection of a reaccelerated thermal muon beam will be used. Since the experimental approaches are different, sources of important systematic uncertainties of the measurements are different, therefore, it is critical to obtain consistent results from the experiments. In this paper, experimental designs, progress, status, and future prospects are discussed.

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The magnetic moment of a spin-1/2 particle is defined as

$$\vec{\mu} = g\frac{Q}{2m}\vec{s}$$

where Q is electric charge, m is mass, $\vec{s}$ is spin, and g is gyromagnetic ratio of the particle, respectively. The gyromagnetic ratio, also called a g-factor, of muon is predicted to be 2 by the Dirac equation, however, it turned out to have deviation from the prediction as quantum loop effects are considered. Therefore, the magnetic moment of muon is written as

$$\vec{\mu} = (1+a_\mu)\frac{e}{2m}\vec{s}$$

where the anomaly, a_μ, is defined as $a_\mu = (g-2)/2$. Contributions to the anomaly come from quantum loop effects such as quantum electrodynamics (QED), electroweak (EW), and hadronic processes. In the Standard Model (SM), the anomaly is written as

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had.}}.$$

Each contribution is well calculated in the framework of the Standard Model. The most recent calculation of the anomaly in the SM is $a_\mu^{\mathrm{SM}} = (11659181.08 \pm 3.78) \times 10^{-10}$ [1], however, the experiment results do not agree with the prediction.

Muon $g-2$ experiment at Brookhaven National Laboratory (BNL) measured the anomaly as $a_\mu = (11659209.10 \pm 6.33) \times 10^{-10}$ [2] which is 3.80 σ away from the SM prediction. Therefore, additional contributions are demanded, and a more precise measurement of the anomaly may be the evidence for the New Physics. The Muon $g-2$ collaboration at Fermi National Accelerator Laboratory (FNAL) [3], the successor of the experiment at BNL, is taking data with the same experimental technique, and is targeting a factor of 5 better sensitivity which will deviate the measurement by $\sim$7 σ away from the SM prediction assuming the same mean value with the BNL result.

One more precision measurement of the anomaly is being developed by the Muon $g-2$/EDM collaboration at Japan Proton Accelerator Research Complex (J-PARC) [4]. It aims for the same level of systematic uncertainty as the one at FNAL with a quite different experimental technique.

The spin of muon precesses under electric and magnetic fields with experimental configurations of $\vec{E}\cdot\vec{B} = 0$ and $\vec{B}\cdot\vec{\beta} = 0$ as

$$\begin{aligned}\vec{\omega} &= \vec{\omega}_a + \vec{\omega}_\eta \\ &= -\frac{e}{m}\left[a_\mu\vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right], \qquad (1)\end{aligned}$$

where $\vec{\omega}_a$ is due to the anomaly, $\vec{\omega}_\eta$ is due to the electric dipole moment (EDM) η, $\vec{B}$ and $\vec{E}$ are magnetic and electric fields, respectively, γ is the Lorentz factor, β is relative velocity to the speed of light c.

In the BNL experiment as well as in the FNAL one the second term vanishes in Eq. (1) by employing a so-called magic momentum ($\gamma \simeq 29.3$) because of the presence of an electric field for a weak focusing of the beam ($\vec{E} \neq 0$).

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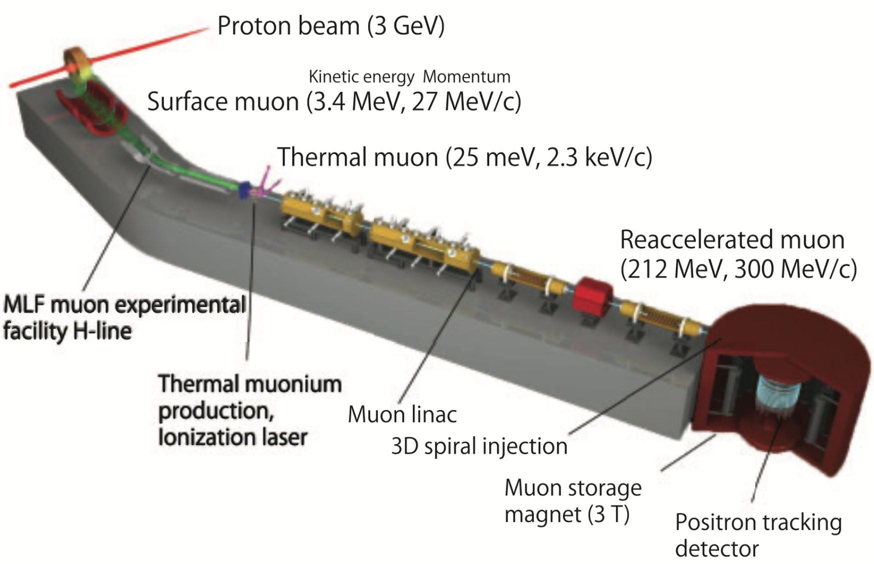

Figure 1: Overview of the J-PARC muon $g-2$/EDM experiment.

On the other hand, the J-PARC experiment does not use an electric focusing ($\vec{E}=0$), therefore, not only the second term vanishes without employing the magic momentum, but also the EDM term becomes simpler.

Figure 1 illustrates the experiment. From a 3 GeV proton beam, a surface muon beam with a momentum of 27 MeV/c and an emittance of about 1000 π mm·mrad is produced and transported to a silica aerogel target. The surface muon produces an atom-like state called muonium ($e^-\mu^+$) by a diffusion process through the target. With Lyman-α lasers with wavelengths of 122 nm and 355 nm, electrons are detached from the muoniums, and thermal muons with momentum of 2.3 keV/c are obtained. Through this process, a low emittance ($< 1\pi$ mm·mrad) muon beam is obtained. Since the muonium emission rate is quite low with a flat silica aerogel target, we have tested various configurations of the target, and found that a laser-ablated silica aerogel target increases the muonium production by an order of magnitude compared to a flat target [5].

The thermal muon beam is reaccelerated up to 300 MeV/c and transported to the storage magnet through a series of accelerator components as shown in Figure 2. From simulations, we do not find a significant emittance growth at the exit of the accelerator. The feasibility of the muon acceleration has been demonstrated with RFQ for the first time in the world [6], and the later components such as IH-DTL [7] will be tested.

The reaccelerated muon beam is injected into the storage magnet with a three-dimensional spiral injection. To store the muon beam, we employ a superconducting magnet of magnetic resonance imaging (MRI) type. The magnet provides a magnetic field of 3 T with a peak-to-peak uniformity less than 100 ppb. It stores the muon beam in the storage region which is defined as $r = 333 \pm 15$ mm and $|z| = \pm 50$ mm from the center of the magnet. To store the muon beam in the storage region vertically, we apply an extra magnetic field with a carefully designed vertical kicker.

Stored muons decay into positrons ($\mu^+ \to e^+\nu_e\bar{\nu}_\nu$), and the detector system detects the positrons. The detector system consists of 40 vanes each containing 16 silicon strip sensors and readouts of

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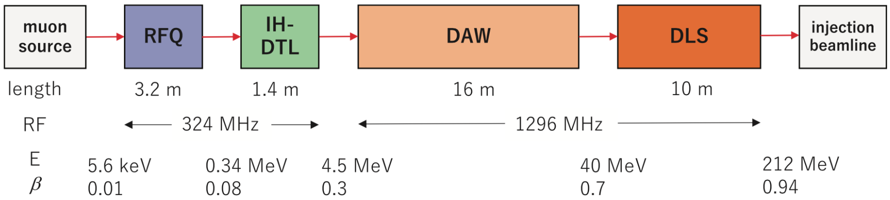

Figure 2: Linear accelerator for the muon reacceleration in the experiment. It consists of a radio-frequency quadrupole (RFQ), interdigital H-type drift tube linac (IH-DTL), disk-and-washer structure (DAW), and disk-loaded traveling wave structure (DLS) for various steps of acceleration.

ASIC frontend boards. The coverage of the detector system is $90 < r < 290$ mm and $|z| < 200$ mm, i.e. full for incoming positrons. Using the hits made by positrons on the sensors, track reconstruction is done, and the efficiency of track reconstruction is found to be more than 90% in an energy window of $200 < E < 275$ MeV from simulation studies.

The magnetic field in the storage magnet is measured by a proton nuclear magnetic resonance (NMR) probe, and it provide a Larmor frequency of proton, $\vec{\omega}_p = \mu_p \vec{B}$, where μ_p is the magnetic moment of proton and $\vec{B}$ is the magnetic field. Using the Larmor frequency of proton, the anomaly of muon can be rewritten as

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}.$$

The ratio of ω_a and ω_p is measured by the experiment, and the ratio of μ_μ and μ_p is employed from other experiment. The current uncertainty of the ratio of the magnetic moment of muon and proton is 120 ppb [8], and a neighboring experiment at J-PARC, the MuSEUM experiment [9], is planned to measure it with a better precision of 10 ppb.

The muon precession, ω_a is measured by fitting the number of detected positrons from the muon decay. For the measurement of the EDM, up-down symmetry

$$\mathscr{A}_{\mathrm{UD}}(t) = \frac{N_+(t) - N_-(t)}{N_+(t) + N_-(t)} = \frac{PA_{\mathrm{EDM}} \sin(\omega_a t + \phi)}{1 + PA\cos(\omega_a t + \phi)}$$

where $N_\pm$ is the number of up/down-going positrons, P is the polarization of the muon, A_{EDM} and A are the effective analyzing powers associated with EDM and of muon decay, respectively, and ϕ is the phase of muon spin. Since the A_{EDM} is associated with the EDM, therefore, it provides an access to the EDM from the experiment.

Assuming 2.2×10^7 seconds of data taking, we expect the statistical and systematic uncertainties on the a_μ measurement to be 450 ppb and $<$ 70 ppb, respectively. Various sources of the systematic uncertainties of ω_a and ω_p are studied and summarized in Table 1. For the EDM measurement, we expect 1.5×10^{-21} e·cm and 0.36×10^{-21} e·cm of statistical and systematic uncertainties with the same data taking time, respectively. The effect of misalignment of the detector is the dominant source of the systematic uncertainty, and the uncertainties from the axial electric field and radial magnetic field are found to be negligible ($< 10^{-24}$ e·cm).

We expect the commissioning run of the experiment in 2023 after constructions of infrastructure and apparatus, and the data taking is expected in 2024.

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Table 1: Estimations of systematic uncertainties of ω_a and ω_p.

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Time shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Differential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

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