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

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This paper describes an experiment based on a new approach to measure the anomalous magnetic moment of muon $a_\mu \equiv (g_\mu - 2)/2$ and the muon electric dipole moment (EDM) d_μ at the J-PARC muon facility. The experiment will utilize a low-emittance muon beam obtained by rf acceleration of thermal muons produced by laser ionization of muonium generated by a silica aerogel target. The use of a low-emittance beam eliminates the need for focusing with an electric field, which has been a factor in introducing large corrections to ω_a measurements in previous and ongoing experiments. The muon beam will be stored in a 3.0 T high uniform field storage ring, which is about one-twentieth the size of the storage ring of the Fermilab. The energy of the decay positrons will be reconstructed using 40 radially aligned silicon strip sensors. The data acquisition is scheduled to begin in 2027. The J-PARC experiment aims to measure a_μ with a precision of 0.45 ppm and search for d_μ with a sensitivity of 1.5×10^{-21} e · cm.

KEYWORDS: muon, J-PARC, $g-2$, EDM

1. Introduction

The Standard Model (SM) [1, 2] is an exceedingly successful theory of elementary particles. While the discovery of the Higgs boson [3, 4] at the Large Hadron Collider (LHC) [5] has made the SM even more reliable as a description of particle interactions, there are still fundamental physical phenomena in nature that are not adequately explained by the SM. In order to obtain clues to physics beyond the SM, various experiments are being conducted.

In such a situation, one of the most promising ways to search for physics beyond the SM is the precise measurement of the anomalous magnetic moment of the muon ($a_\mu \equiv (g_\mu - 2)/2$, where g_μ is the Landé g-factor of the muon). The experimental value of a_μ was known to be

$$a_\mu(\mathrm{BNL}) = 116592080(63) \times 10^{-11}\ (0.54\ \mathrm{ppm}), \tag{1}$$

from precise measurements performed at Brookhaven National Laboratory (BNL) by 2001 [6]. After that, re-measurement has been carried out at Fermi National Accelerator Laboratory (FNAL) since 2018, and the result

$$a_\mu(\mathrm{FNAL}) = 116592040(54) \times 10^{-11}\ (0.46\ \mathrm{ppm}), \tag{2}$$

based on the 2018 data was published in 2021 [7]. The combined experimental average [7] is

$$a_\mu(\mathrm{Exp}) = 116592061(41) \times 10^{-11}\ (0.35\ \mathrm{ppm}). \tag{3}$$

On the other hand, the Muon $g-2$ Theory Initiative recommended value for the SM prediction of a_μ [8] is

$$a_\mu(\mathrm{SM}) = 116591810(43) \times 10^{-11}\ (0.37\ \mathrm{ppm}). \tag{4}$$

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The discrepancy between the experimental value and the theoretical value,

$$\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}, \tag{5}$$

has a significance of 4.2σ, which is attracting attention as a possible sign of new physics.

The muon electric dipole moment (EDM) d_μ is also valuable to study. A non-zero EDM of an elementary particle violates time-reversal symmetry, and assuming the CPT-theorem, it also violates the combined symmetry of charge conjugation and parity inversion. Moreover, in the SM, the EDM of leptons is so small that their detection, if it exists at all, is predicted to be far beyond experimental capabilities for the foreseeable future. Therefore, any experimental non-zero muon EDM value would indicate the existence of new physics. The current limit on the muon EDM of $|d_\mu| < 1.8 \times 10^{-19}$ e $\cdot$ cm (95% C.L.) was set by the BNL muon $g-2$ collaboration [9].

2. Experimental approaches

In the $g-2$ experiment, a spin-polarized muon is orbited in the magnetic field of a storage ring to obtain information on the time evolution of spin precession. In the presence of the static magnetic field $\vec{B}$ and electric field $\vec{E}$, with the case that muon velocity $\vec{\beta}$ is perpendicular to both $\vec{B}$ and $\vec{E}$, the anomalous precession frequency $\vec{\omega}_a$ defined as the difference of the spin precession frequency $\vec{\omega}_s$ with respect to the cyclotron frequency $\vec{\omega}_c$ is given by,

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu\vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{6}$$

where e is the elementary charge, m_μ is muon mass, γ is the Lorentz factor, c is the speed of light. The first term is the precession due to the magnetic field, and the second term is the precession due to the effective magnetic field proportional to $\vec{\beta}\times\vec{E}$ which relativistic particles feel. In the "magic momentum" approach used in the BNL and FNAL experiments, the second term in eq. (6) is reduced to zero by choosing the muon central momentum of 3.094 GeV/c, or $\gamma = \sqrt{(1 + 1/a_\mu)} \approx 29.3$, and it can be rewritten into the following simplified form,

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -a_\mu\frac{e\vec{B}}{m_\mu}. \tag{7}$$

On the other hand, in the Japan Proton Accelerator Research Complex (J-PARC) experiment [10], the second term in eq. (6) is eliminated by not using the focusing electric field at all. In this case, eq. (6) is similarly simplified to eq. (7). Therefore, in both methods, in order to determine a_μ precisely, it is necessary to know the $\vec{\omega}_a$ frequency and the magnetic field $\vec{B}$ with high precision. The former is obtained by measuring the modulation of the decay positron energy spectrum as the muon orbits in the ring, while the latter is measured by nuclear magnetic resonance (NMR) techniques.

If the muon has an EDM, eq. (7) can be rewritten as the following form with the addition of the spin precession term due to the EDM ($\vec{\omega}_{EDM}$),

$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu\vec{B} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right] = \vec{\omega}_a + \vec{\omega}_{EDM}, \tag{8}$$

where η is a dimensionless parameter directly proportional to the magnitude of the muon EDM. In the $g-2$ measurement experiments, the magnetic field is applied perpendicular to the muon orbit in general, so $\vec{\omega}_a$ and $\vec{\omega}_{EDM}$ are orthogonal. Therefore, since the precession plane of the muon spin will be tilted, the EDM can also be measured by making the measurement sensitive to this tilt.

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3. The J-PARC experiment

3.1 Overview

The muon $g-2$ experiment at J-PARC aims to perform an independent measurement of a_μ using a completely different approach from the BNL and FNAL experiment. In the experiment, a low-emittance 300 MeV/c muon beam, which is produced by re-accelerating thermal muons generated by laser ionization of muonium (bound state of μ^+ and e^-) emitted from silica aerogels, will be used. By virtue of the low emittance of the muon beam, there is no need for focusing with the electric field which can cause large corrections and systematic errors in $\vec{\omega}_a$ measurements in the BNL and Fermilab experiments. The muon beam will be stored in a highly uniform magnetic storage ring with a small radius. The energy of the decay positrons will be reconstructed silicon strip sensors. Figure 1 shows the schematic view of the J-PARC experiment. The data acquisition is scheduled to begin in 2027. The experiment is expected to achieve statistical uncertainty of 0.45 ppm for a_μ and sensitivity of 1.5×10^{-21} e · cm for muon EDM, assuming a data acquisition time of 2.2×10^7 seconds with a 1 MW proton beam and 50% μ^+ polarization. The following subsections describe each component.

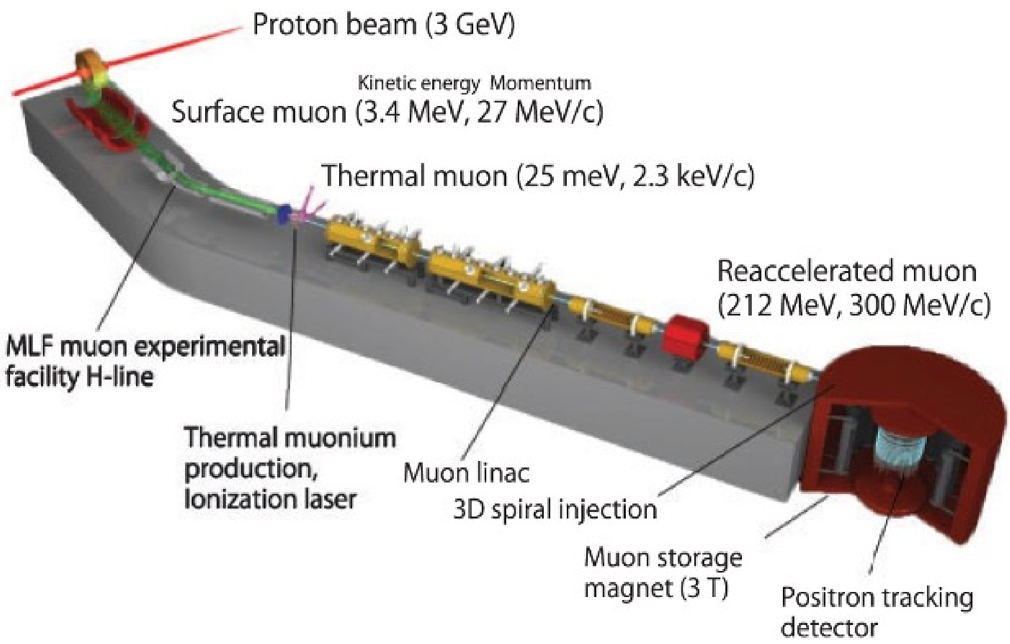

Fig. 1. Schematic view of the muon $g-2$/EDM experiment at J-PARC [10].

3.2 Experimental facility & beam line

The experiment will be conducted at the Material and Life Science Experimental Facility (MLF) of J-PARC in Tokai, Japan. A proton beam of 3 GeV kinetic energy with 1 MW beam power is delivered from the rapid-cycling synchrotron (RCS) to MLF and injected into the 2 cm thick graphite target to generate pulsed muon beams. The proton beam has a double-pulse structure, and each pulse is 100 ns in width (FWHM) with a 600 ns separation and 25 Hz repetition rate. A surface muon beam with a momentum centered around 27 MeV/c will be extracted. There are four beamlines extracting muon beams. One of the beamlines, called H-line, employs a large capture solenoid magnet to provide a high-intensity muon beam. The muon beam intensity is expected to be 10^8 per second with 1 MW proton beam. The H-line is currently under construction and the first beam commissioning is scheduled for early 2022.

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3.3 Thermal muon production

The surface muon beam extracted to H-line is stopped in a laser-ablated silica aerogel target [11, 12]. In the target, most of the muons form muonium and then the muonium diffuses out to the vacuum region. The muonium emitted to the vacuum region is ionized by a laser and a thermal muon beam is produced. Two types of ionization scheme have been developed. One is based on the 1S-2P transition by one-photon excitation, and the other is based on the 1S-2S transition by two-photon excitation. A muonium ionization test using the latter scheme is scheduled for early 2022.

3.4 Muon acceleration

The generated thermal muons are accelerated to 5.6 keV by an electrostatic field and injected into a radio-frequency quadrupole (RFQ). The muons injected into the RFQ are accelerated to 0.34 MeV. Then, the energy of the muon beam is boosted to 4.5 MeV with an interdigital H-mode drift tube linac (IH-DTL). Following the IH-DTL, a disk-and-washer coupled cavity linac (DAW CCL) are used to accelerate the muons to 40 MeV. Finally, the muons are accelerated from 40 MeV to 212 MeV by using a disk-loaded traveling wave structure (DLS). Figure 2 shows the schematic configuration of the muon linac. Recently, demonstration of muon acceleration using a RFQ has been succeeded for the first time in the world [13]. Currently, the fabrication of RF cavities is progressing sequentially from the upstream side of the linac.

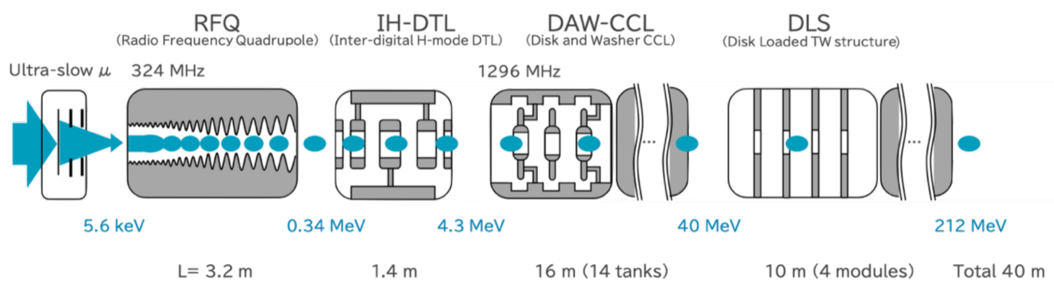

Fig. 2. Configuration of muon linac.

3.5 Muon storage magnet & beam injection

A 3 T MRI-type superconducting solenoid magnet [14] will be used to inject and store the accelerated muon beam. The cyclotron radius is 333 mm, which is about a factor of 20 smaller than that for the BNL/FNAL experiments. The muons are stored in the highly uniform magnetic field with peak-to-peak 0.1 ppm local uniformity. Several systems have been developed to measure and monitor the magnetic field with the required accuracy.

In our experiment, the radius of the beam orbit in the storage magnet is too small to kick horizontally into the storage region as in previous experiments. A three-dimensional spiral injection scheme [15] has been developed in order to inject the muon beam into the storage magnet. This new injection scheme will enhance injection efficiency and overcome technical challenges related to the small storage orbit radius. The injection efficiency is expected to be 85%. A test bench using electron beams has been developed and demonstration tests are currently underway.

3.6 Positron tracking detector

Positrons from decay of stored muon beam are detected by the detector [16] installed in the storage magnet. The detector is required to detect positrons with momenta above 200 MeV/c with high efficiency, and to reconstruct their tracks in a 3 T magnetic field to determine their momenta and decay times. The detector consists of 40 modules called vanes (composed with four quarter vanes)

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with silicon strip sensors for positron detection. A mechanical prototype and an electrical prototype will be fabricated within FY2021 aiming to consider the assembling method and to test electrical operation respectively.

4. Summary

The muon g-2/EDM experiment at J-PARC with a new method is planned. Various preparations for the experiment are steadily underway. In this paper, the overall design of the experiment and its preparation status is described. The experiment is expected to start in 2027 with a target precision of about 0.5 ppm.

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