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

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The recent measurement of the muon anomalous magnetic moment, $a_\mu = (g_\mu - 2)/2$, with a precision of 0.46 ppm at the Fermilab National Accelerator Laboratory (FNAL) confirmed the anomaly observed at the Brookhaven National Laboratory (BNL) from more than a decade ago. The value of this anomaly between the measurements and the Standard Model (SM) prediction has been reported to be 4.2 standard deviations. Though this may indicate the existence of new physics beyond the SM, it should be verified through other measurements. The J-PARC experiment aims to measure a_μ and the electric dipole moment (EDM) in a completely different way from the BNL and FNAL experiments, using a low-emittance muon beam realized through the acceleration of the thermal muons. This paper reports the current status of each experimental component.

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1. Introduction

The discovery of the Higgs boson using the Large Hadron Collider (LHC) has established the Standard Model (SM) as the most successful description of particle interactions. However, we are still confronted with several problems that can be solved only through experiments. With no signs of new physics in the LHC, it is clear that multiple experimental approaches are required. Among them, indirect searches for new physics through precision measurements has been playing an increasingly significant role because indirect searches can reach a higher energy scale when compared with direct search. One of the most interesting methods is the precise measurement of a_μ = $(g_\mu - 2)/2$, where the discrepancy between the SM prediction and the measurement has remained unresolved for more than a decade. A recent measurement of a_μ with a precision of 0.46 ppm at the Fermilab National Accelerator Laboratory (FNAL) [1] confirmed the anomaly from the preceding Brookhaven National Laboratory (BNL) experiment [2]. Now the gap between the measurements and the SM prediction [3] has become 4.2 standard deviations.

Because the muon beam generated from the secondary pions has a large emittance, a strong focusing electric field in addition to the magnetic field is necessary in a storage ring. The difference between the cyclotron motion frequency ($\vec{\omega}_c$) and the muon spin precession frequency ($\vec{\omega}_s$) is expressed as follows:

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

where e is the elementary charge, m is the muon mass, a_μ is the anomalous magnetic moment, γ is the Lorentz factor, β is the ratio of particle velocity to the speed of light c, and η is the electric dipole moment. The second term, which depends on the electric field, is eliminated when the momentum of the muon is 3.094 GeV/c, referred to as the magic momentum. Both the BNL and FNAL experiments employ the technique knows as magic momentum.

The J-PARC E34 experiment [4] aims to measure a_μ with a precision of 0.1 ppm and search for the elecric dipole moment (EDM) with a sensitivity of approximately $10^{-21}\,e\cdot$cm using a method completely different from that used in the BNL and FNAL experiments; it is realized using a low-emittance muon beam. Figure 1 depicts the experimental setup. The pulsed high-power primary proton beam generates secondary surface muons. The produced surface muons are extracted and become thermalized to form muoniums (μ^+e^-), which are then emitted into the adjacent vacuum region. The paired electron in the muonium is knocked out by a laser, and a thermal muon (3 keV/c) is generated. After acceleration to 300 MeV/c, the muon beam has extremely low emittance such that it can be injected and stored in a high-precision compact storage magnet, where the time dependence of the number of positrons from muon decay is measured. Owing to the low-emittance of the muon beam, the electric focusing is not necessary anymore. Eq. 1 can then be rewritten as follows:

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

Since the precession vectors due to the anomalous magnetic moment and EDM are orthogonal, these can be measured simultaneously.

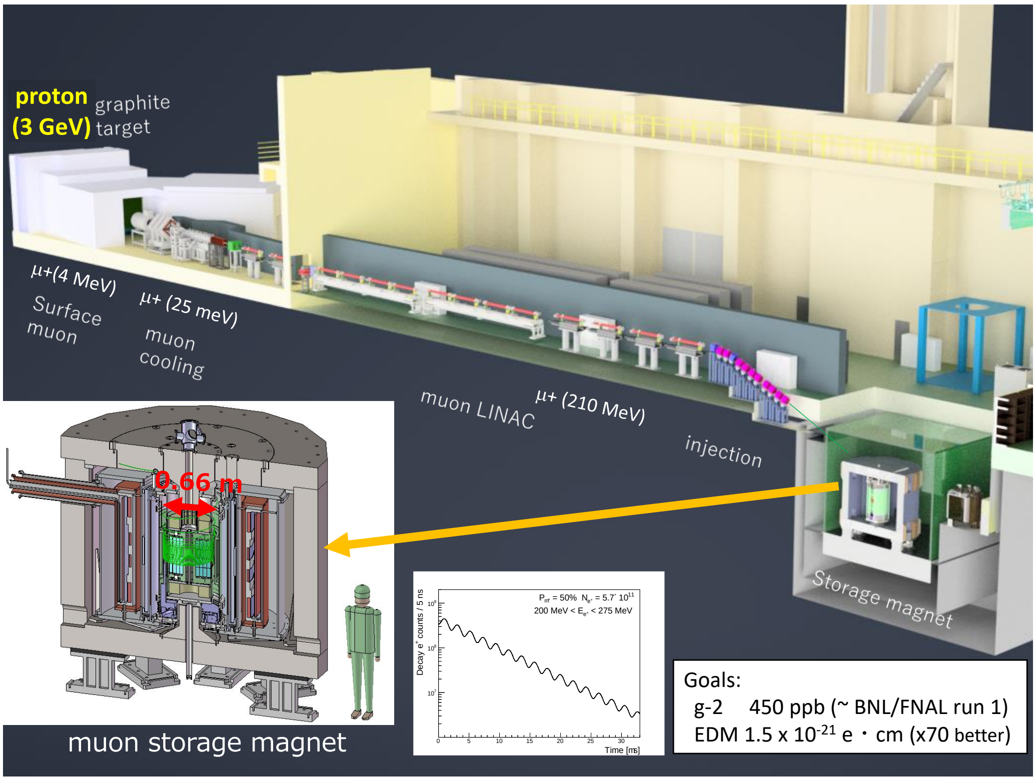

Figure 1: Overview of the J-PARC E34 experiment.

2. Experimental Components

The J-PARC accelerator comprises a 400-MeV H^- linac, 3-GeV rapid-cycling synchrotron (RCS), and 30-GeV main ring. The experiment is conducted in the Materials Life Science Experimental Facility (MLF), which uses a 3-GeV proton beam from the RCS to produce muons. At present, the J-PARC linac provides beams with a designed peak current of 50 mA and the RCS provides a beam power of 700 kW to MLF. The RCS has successfully demonstrated 1-MW beam operation for 36h in the summer of 2020. The beam power at MLF is scheduled to be gradually increased to the primary goal of 1 MW for use in the experiments.

The generated surface muons are extracted to a muon beam line known as the H-line, which adopts a large-aperture capture solenoid magnet for supplying a high-intensity muon beam [5]. The H-line is under construction and the first beam commissioning is scheduled in early 2022.

The surface muons are injected and stop in a silica aerogel target, and a portion of the muons form thermal muonium. By using silica aerogel with a submillimeter structure fabricated using a femtometer laser, the muonium emission was enhanced by approximately one order of magnitude when compared with the target having no structure [6, 7]. After diffusing into a vacuum region, the muoniums are ionized by the laser. Two types of ionization scheme, unbound via $1s$ to $2p$ and $1s$ to $2s$, have been developed. The latter scheme will be tested in early 2022.

Because a muon has a finite lifetime, it should be accelerated in a sufficiently short period of time to suppress the loss owing to decay. To realize fast acceleration, a muon-dedicated linear accelerator (linac) consisting of four types of radio-frequency cavities, as depicted in Fig. 2, has been developed. Recently, we succeeded in demonstrating muon acceleration using a radio-frequency quadrupole for the first time [8]. The upstream part of the muon linac has been produced based on the experiences of the prototypes [9].

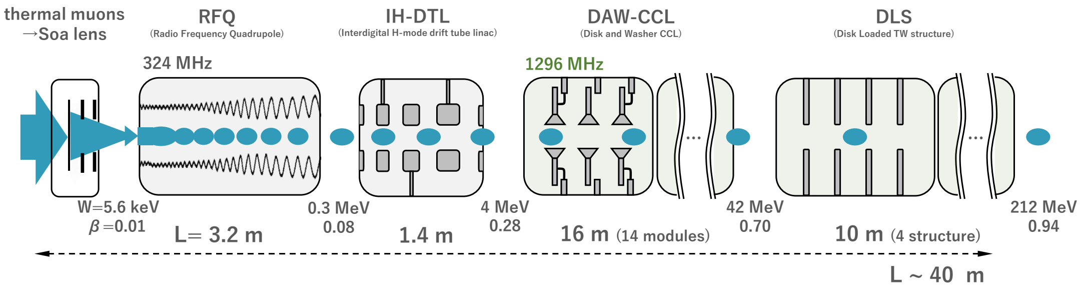

Figure 2: Configuration of the muon linac. W represents the kinetic energy and β represents the ratio of the muon velocity to the speed of light.

Due to the small radius of the beam trajectory and the limited space of the storage magnet, the muon beam can not be injected into the storage region by the method used in the previous experiments of horizontal injection. Instead, the muons pass in a downward direction through a small entrance hole in the upper steel yoke of the storage magnet and reach the storage region after the remaining vertical momentum is adjusted by a pulsed radial magnetic field. The transport-beamline was designed to match the acceptance of this spiral injection scheme [10]. A test bench using a 300-keV electron beam is now being developed to demonstrate the spiral injection scheme.

The storage magnet consists of four superconducting coils supplying a main field of 3 T with peak to peak 0.1 ppm local uniformity. In order to achieve high homogeneity of the magnetic field below 0.1 ppm, the field imperfections is corrected by shimming with iron pieces inside the magnet bore and superconducting shimming coils [11]. Several systems have been developed to measure and monitor the magnetic field with required accuracy [12].

The decay positron detector is required to be highly segmented and operate in a field of 3 T. To satisfy these requirements, the silicon strip detectors are radially placed in the detection volume to efficiently detect the circular track of the positrons. The final version of the front-end ASIC was developed for the detector referred to as SliT [13, 14] and delivered at the end of March 2021.

All the experimental components were designed based on measurements or, if not possible, simulations. Based on an estimation of the intensity, the statistical uncertainty of 0.45 pmm will be achieved assuming a total running time of 2×10^7 s with a muon polarization of 0.5. In addition, the EDM will be measured with a statistical uncertainty of 1.5×10^{-21} e·cm. Because the systematic uncertainty was estimated to be less than 70 ppb and the measurement is statistically limited, further improvement of the beam intensity would directly impact the sensitivity of the physics. Because improvement is required primarily in the muonium emission efficiency, the arrangement of the silica aerogel target is being investigated to enhance the overlap between the effective area of the target and the laser ionization region.

3. Summary

A precise measurement of a_μ is a promising path to the establishment of new physics beyond the SM. The J-PARC E34 experiment aims to measure a_μ and muon EDM with high precision and sensitivity using the newly developed novel method employing a low-emittance muon beam. The statistical uncertainties for our Phase 1 measurement are estimated to be 0.45 ppm and 1.5×10^{-21} e·cm for a_μ and the muon EDM, respectively.

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References

[1] B. Abi *et al.*: Phys. Rev. Lett. **126** (2021) 141801

[2] G.W. Bennett *et al.*: Phys. Rev. D **73** (2006) 072003

[3] T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum *et al.*: Phys. Rep. **887** (2020) 1

[4] K. Abe *et al.*: Prog. Theor. Exp. Phys., **053** (2019) C02

[5] N. Kawamura *et al.*: Prog. Theor. Exp. Phys., **113** (2018) G01

[6] G.A. Beer *et al.*: Prog. Theor. Exp. Phys., **091** (2014) C01

[7] J. Beare, K. Suzuki *et al.*:, Prog. Theor. Exp. Phys. **123** (2020) C01

[8] S. Bae *et al.*: Phys. Rev. Accel. Beams **21** (2018) 050101

[9] Y. Nakazawa *et al.*: J. Phys. :Conf. Ser. **1350** (2019) 012054

[10] H. Iinuma *et al.*: Nucl. Instrum. Meth. A **832** (2016) 51-62

[11] M. Abe *et al.*: Nucl. Instrum. Meth. A **890** (2018) 51-63

[12] H. Yamaguchi *et al.*: IEEE Trans. Appl. Super., **29** (2019) 9000904

[13] T. Kishishita *et al.*: IEEE Trans. Nucl. Sci., **67(9)** (2020) 2089

[14] Y. Sato *et al.*: Nucl. Instrum. Meth. A **969** (2020) 164035