PROCEEDINGS OF SCIENCE

J-PARC g-2/EDM preparations and prospects

D Samuel, for the J-PARC E34 Collaboration[a,*]

[a] *Department of Physics,*
Central University of Karnataka, India

E-mail: deepaksamuel@cuk.ac.in

Muon g-2 measurements provide a glimpse into physics beyond the standard model, beginning with the pioneering experiments in the 1960s. Over the years, advancements in measurement techniques have steadily reduced uncertainties. Despite these efforts, recent results from theoretical predictions and experimental observations have shown disagreements. In this context, a new experiment is planned at J-PARC, employing a low-emittance muon beam to minimize systematic uncertainties. In this presentation, I will outline the measurement techniques employed and discuss the progress achieved on multiple fronts in this ongoing endeavor.

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1. Introduction

A comparison of the latest Run-2/3 results of the Fermilab muon g-2 experiment on the muon anomalous magnetic moment a_μ, with the Muon Theory Initiative white paper 2020, shows a difference of 5.1 standard deviations. This has received massive attention from the community [1] [2]. On the other hand, tensions from the theory side arising from hadronic contributions to a_μ have precluded a firm confirmation of this deviation between measurements and theory. In this context, a complimentary and independent measurement of a_μ will be important to gain clarity and resolve ambiguities. The J-PARC muon g-2 experiment is a proposed experiment that intends to measure the anomalous magnetic moment and the electric dipole moment (EDM) of the muon with a different systematic uncertainty [3]. In this report, a brief overview of this experiment along with its status and prospects is presented.

2. Background

The precession of the muon's spin in an electromagnetic field, with respect to its cyclotron motion is given as:

$$\vec{\omega} = -\frac{e}{m}[a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c})] \quad (1)$$

where, ω is the spin precession frequency, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields experienced by muon, respectively, γ is the Lorentz factor, and η is the muon EDM. One measures a_μ through a measurement of ω, in known electric and magnetic field configurations. Consequently, uncertainties in these fields also translate into uncertainties in a_μ. The precise measurement of the fields experienced by the particle in its orbit on the storage volume is an experimental challenge. E-fields are required to focus the beam in the storage volume in the Fermilab experiment. To minimize the effect of E-field uncertainties, the Fermilab experiment uses the so-called *magic gamma* approach, in which the beam momentum (3.094 GeV/c) is suitably chosen such that a_μ is approximately equal to $\frac{1}{\gamma^2-1}$. At this momentum, the value of γ is 29.3.

The J-PARC muon g-2 experiment eliminates the requirement for E-field by using a low-emittance muon beam produced by re-accelerated thermal muons [3].

3. Comparison of Experiments

Table 1 presents a comparison of few experimental parameters from previous experiments with the J-PARC experiment. The muon momentum is about a factor 10 lower than in previous experiments, decreasing γ to 3. The statistical precision of the measurements is inversely proportional to the product of γ and B, which impacts the sensitivity of the J-PARC experiment. However, this is compensated to some extent by the increase in samples due to a high beam power of 1 MW and a higher magnetic field of 3 T. The storage volume is smaller in size, enabling better control and design of the storage magnet.

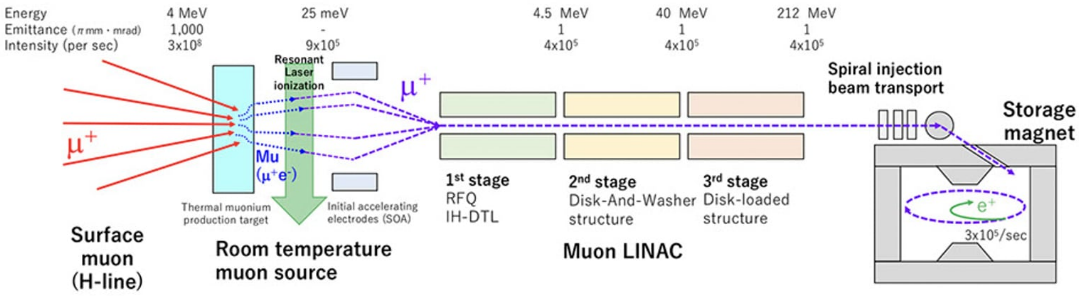

Figure 1: Schematic of the experimental setup.

	BNL-E821	Fermilab-E989	J-PARC
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Lifetime $\gamma\tau_\mu$		64.4 μs	6.6 μs
Polarization	100%		50%
Storage field	B=1.45 T		B=3.0 T
Radius of cyclotron motion	7.1 m		333 mm
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
a_μ precision (sys.)	280 ppb	100 ppb	$\ll$ 70 ppb
EDM precision (stat.)	0.2×10^{-19} e · cm	–	1.50×10^{-21} e · cm
EDM precision (sys.)	0.9×10^{-19} e · cm	–	0.36×10^{-21} e · cm

Table 1: Comparison of parameters from previous experiments with the J-PARC experiment. The E989 experiment uses the same storage ring magnet from E821. Empty cells in E989 indicate the same values as in the corresponding cells for E821.

4. Experimental setup

A proton beam of 3 GeV hits a graphite target to produce surface muons, which are transported and captured in a muonium production chamber to produce Mu atoms. At this point, the muons are thermalized to an energy of 25 meV. Mu states are then ionized by a laser to produce positive muons that are accelerated by a LINAC and injected into the storage volume. The muons orbit in a magnetic field with a local uniformity of about 1 ppm. Figure 1 displays the schematic of the experimental setup. The central region of the storage volume contains a positron detector consisting of 40 vanes of silicon strip sensors. A sensor has two blocks of 512 strips with a pitch of 190 µm and each vane has 16 sensors, 8 each to measure the radial position and 8 for axial positions.

5. Measurement

As the positive muons circulate in the storage volume, they decay into positrons that then enter the central region. We use the positron tracks formed in the detectors to determine the decay position and time which are then used to create the *wiggle plots*. The period of oscillations in the *wiggle plot*, with an appropriate energy criterion, gives direct information on the value of a_μ. We can also measure the muon EDM by analyzing the up-down asymmetry of the decaying positrons. At present, the current challenge is how to find the tracks under pileup conditions. We currently use a Hough-transform-based algorithm, but to match the muon rate, we need to improve the computation time by a factor of 40.

6. Uncertainties

Contributions to statistical uncertainty come from several sources. The efficiency in muonium emission is low, at about 0.0034. Various activities are in progress to improve this factor. The efficiency in H-line acceptance and transmission is approximately 0.16. Furthermore, an important contribution comes from the positron energy window. This is required as only the direction of maximum-energy positrons correlates with the muon spin. The efficiency of this process is about 0.12. The overall muon efficiency is expected to be 1.3×10^{-5}, and with a total of 5.7×10^{11} muons, the overall statistical uncertainty is expected to be 450 ppb. The systematic uncertainties come from two sources: one from the anomalous spin precession and another from the magnetic field estimation. Uncertainty due to timing shifts dominates the former, while the position of the magnetic probes dominates in the latter. We expect the total systematic uncertainty to be 70 ppb.

7. Status

There are several activities ongoing to meet the data-taking deadline in 2028. We are currently discussing how to improve muonium emission efficiency using laser- ablated aerogel. Additionally, two options for thermal muonium ionization by laser are being considered. One strategy is use a 1S-2P excitation by a 122 nm laser and the other is to use a 1S-2S excitation by a 244 nm laser. The muon reacceleration in a LINAC is achieved in several stages. In the low-β stage, the acceleration test with thermal muons of RFQ was planned for 2023, and the fabrication of IH-DTL has been completed. The middle-β DAW-CCL tank fabrication is currently under progress, and the high-β DLS prototype was fabricated in 2022. On the detector front, major components are either in or have completed mass production, and the assembly procedure is under development. The quarter vane prototype is currently undergoing a readout electronics test. On the analysis side, work is ongoing on sensor alignments and the development of fast and efficient track-finding algorithms is under active development.

8. Summary

Using a complementary approach, the J-PARC muon g-2 experiment aims to measure the anomalous magnetic moment of the positive muon and its electric dipole moment. It intends to

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measure a_μ with a precision of 450 ppb and a systematic uncertainty of 70 ppb. Many activities are currently in progress, and it is expected that the experiment will meet the 2028 deadline.

References

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