New $g-2$ experiment at J-PARC

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Abstract A new measurement of the anomalous magnetic moment of the positive muon a_μ is proposed with a novel technique utilizing an ultra-cold muon beam accelerated to 300 MeV/c and a 66 cm-diameter muon storage ring without focusing-electric field. This measurement will be complimentary to the previous measurement that achieved 0.54 ppm accuracy with the magic energy of 3.1 GeV in a 14 m diameter storage ring. The proposed experiment aims to achieve the sensitivity down to 0.1 ppm.

Key words muon, anomarous magnetic moment, J-PARC

PACS 13.40.Em, 12.15.Kk, 14.60.Ef

1 Introduction

The study of magnetic moments has played an important role in our understanding of fundamental lws in physics as well as broad range of applications. The anomalous magnetic moment of the muon ($a_\mu=(g-2)/2$) is directly sensitive to the electromagnetic, strong, weak forces, as well as possible extensions of the Standard model [1]. The present experimental value for muon $g-2$ is from the E821 experiment at BNL, which achieved a sensitivity of 0.54 ppm [2, 3]. This measured value, $a_\mu=0.001165\,92080$ (54) (33), disagrees with the calculated value by more than 3 standard deviations [4, 5].

The spin orientation of the longitudinally polarized muon will follow its momentum direction when it is stored in the static electro-magnetic field, $\vec{B}$ and $\vec{E}$. The anomalous magnetic moment a_μ introduces an additional precession with its precession vector $\vec{\omega}_a$ given by

$$\vec{\omega}_{\rm a}=-\frac{e}{m_\mu}\left[a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]. \qquad (1)$$

Since $a_\mu\sim\alpha/(2\pi)\sim0.00116$, a choice of "magic" energy, $\gamma=29.4$ would reduce the above formula to an extremely simple form, $\vec{\omega}_{\rm a}=-\frac{e}{m_\mu}a_\mu\vec{B}$. Therefore, precision measurement of $\vec{\omega}_{\rm a}$ in the precision field $\vec{B}$ will provide precision determination of a_μ.

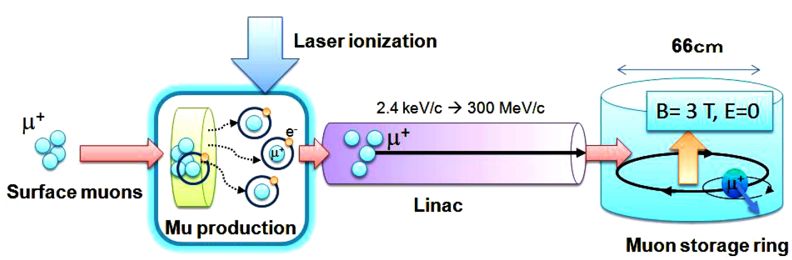

Fig. 1. Overview of the experiment.

Received 25 January 2010

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It should be emphasized that the success of the E821 experiment stimulated significant progress of e^+e^- experiments and related theories as it was largely discussed in this conference. New high precision e^+e^- data has been released from CMD-2, SND, KLOE, and Babar. On the other hand, the precision measurement of a_μ is only available from the E821. While the new proposal to continue the E821-type experiment at FNAL [6] is important and promising, we believe that it is valuable to launch yet another new experiment to measure this fundamental quantity with a completely new experimental technique, thus providing a completely independent measurement.

The overview of the experiment is shown in Fig. 1. The goal for this new experiment is to reach the sensitivity of a_μ down to 0.1 ppm level.

2 New $g-2$ experiment

Other than running at the magic energy, there is another approach to avoid the complication of Eq. (1), i.e. elimination of the electric field. We propose to measure the muon $g-2$ without the focusing electric field by employing ultra-cold muon beam, where the transverse momentum dispersion, $\sigma(p_T)$ is significantly smaller than its longitudinal momentum, p_L. Such a beam can circulate in the storage ring without the focusing field for the duration of the measurements. Elimination of the electric field would greatly simplify the precession frequency as $\vec{\omega}_a = -\frac{e}{m_\mu} a_\mu \vec{B}$. Or it can be written as follows by introducing explicit contribution from the electric dipole moment

$$\vec{\omega_a} + \vec{\omega_\eta} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right], \qquad (2)$$

where η is the electric dipole moment, and ω_η is its precession vector. Since the rotation axes due to a_μ and η are orthogonal, separation of these signals should be possible.

We consider the case with

$$\frac{\sigma(p_T)}{p_L} \sim 10^{-5}, \qquad (3)$$

with the $B=3$ T and $p=300$ MeV/c, which corresponds to $r=33.3$ cm. Five times its dilated lifetime of muon (5×6.6μsec) corresponds to travel length of 8 km, or about 4000 turns. The beam spread due to the transverse momentum dispersion in Eq. (3) is 80 mm after 4000 turns, which can be easily accommodated in the storage field.

Such an ultra-cold beam can be produced from an ultra-cold muon source, where cold muons are produced from the resonant laser-ionization of muonium (Mu). The kinetic energy of the Mu is ∼25 meV (momentum∼ 2.4 keV/c), when produced at room temperature. If we could accelerate them to 300 MeV/c without further increase in the transverse momentum, the Eq. (3) is satisfied. Since we have no electric field, the $\vec{\beta}\times\vec{E}$ term in Eq. (1) does not exist so that any momentum can be "magic" momentum, which was not the case for previous experiments [2, 7–9] as well as the new FNAL experiment [6].

While higher momentum is helpful in prolonging the life of muons, lower momentum is beneficial in reducing the size of the experimental apparatus, and hence the cost of the experiment. However, the most important benefit emerges from the fact that such a small magnet for a muon precession measurement can be made in one piece enabling us to control the field in a great precision. Thanks especially to the recent advances in the magnetic resonance imaging (MRI) technology, the precision monitoring and control of the magnetic field of ∼1 m diameter region has reached to 1 ppm precision. This precision can be compared to a local magnetic-field precision of the previous measurement, ∼100 ppm while the field precision integrated over full muon trajectory was better than 1 ppm[2].

2.1 Ultra-cold muon beam

The ultra-cold muons will be produced in the following sequence. At the J-PARC [10], the 3 GeV proton beam, running at 25 Hz, will hit the Muon graphite target in the M2 tunnel at Material and Life Science Facility (MLF), and produce pions which will be stopped in the target. Those π^+ that stop on the surface of the target decay to 4 MeV μ^+, which will be collected using a large-aperture capture solenoid, and followed by transport-curved solenoid, to a Mu production target.

The transported surface muons will stop in the Mu production target, and form Mu (μ^+-electron atoms). The Mu behaves like hydrogen atoms and diffuses from the target. It is important that this target be at room temperature (300 K ∼ 25 MeV) so that the Mu atoms drift slowly.

Pulsed lasers with 122 nm (Lyman-α) and 355 nm wavelength will ionize the Mu at around the target surface, producing ultra-cold polarized muons. The muons are then accelerated by two linacs to reach the energy of 320 MeV. The expected transverse dispersion of this beam is 10^{-5}. The expected beam intensity is 4 $\times 10^4$/pulse.

In the following, present status and projected research plan is discussed. At J-PARC, surface muon signals have already been observed from the M2 Muon target with the flux that is equivalent to or higher than RAL-ISIS. The muon facility in the MLF has been routinely providing muon beams to the material science users. One of the four beamline ports in the MLF is considered to build the ultra-cold muon beamline for this experiment.

The room-temperature Mu production target must be selected to achieve the transverse dispersion of 10^{-5}. Silica powder has been known to produce Mu at room temperature [11–13]. For the purpose of laser ionization, a solid target which is self-standing and has well-defined surface, is preferred over powder target. However not much studies has been performed on the solid targets. In maximizing number of Mu and ionized muons, it is important to know the spacial as well as time evolution of the Mu atoms drifting downstream of the target. Solid materials with nano-structure are candidates for a good Mu emitter. Examples of such are silica-aerogels, micro-channeled SiO_2, and Cs-/Na-coated W. An experiment to study the target material for Mu production is scheduled at TRIUMF in 2010 [14].

The technique of laser ionization of Mu has been developed by KEK and RIKEN [15], and continuously improved at the RIKEN-RAL muon facility [16]. The efficiency to produce the ultra-cold muon from the surface muon beam is 3×10^{-5} at RAL. A new laser system is currently under development at RIKEN to increase the laser power by a factor of 100. With the 100 times intense laser, we expect the efficiency to be two orders of magnitude higher, i.e. 3×10^{-3}, which will be examined by the test experiments at RAL and J-PARC.

The default polarization of the ultra-cold muon is 50%. R&D to improve the polarization is in progress based on the ideas of introduction of a longitudinal magnetic field, or a narrow band laser.

Initial acceleration will use the weak static electric field, followed by double einzel lenses, the static acceleration field, a re-buncher, and a focusing elements. Cooling of the muon beam even below the room temperature would be possible by utilizing a chirped-laser.

The linac designs utilizes existing technologies developed for J-PARC and KEK-B accelerators. The linacs used to accelerate the cold muons are essentially a proton-type linac at lower β using a Drift-Tube Linac (DTL), and an electron-type linac (disk-loaded type with pitch adjusted for β) at higher β.

2.2 Muon injection and storage

The ultra-cold muon beam will be injected to the precision magnetic storage ring which consists of a 3 T solenoid with 66 cm-diameter, a anti-Helmholz type kicker, and a magnetic field monitor system. The magnetic field shape of the solenoid is designed so that the muon beam is injected into the storage ring from the upper side of the solenoid magnet by making a vertical spiral trajectory. Spirally-falling muons are stopped in the storage region by the anti-Helmholz type kicker with 150 ns pulse full width (half-sine) and 1.3 Gauss. The magnetic field in the storage region is carefully simed by the correction coils to achieve the field uniformity of 0.1 ppm level. The absolute magnitude of the magnetic field is periodically mapped by the NMR proving system. Hall proves stationary monitors the magnetic field in the storage ring.

We have started a conceptual design of the ultra-precision field employing technology developed for MRI. We expect to have an engineering drawing in a year so that construction would start in about one year. The measurement scheme with NMR probes is being developed at this time. A test of this technique at 1.5 T is planned, followed by a test in a 3 T magnet at National Institute of Radiological Science (NIRS).

2.3 Detection of decay positrons

After injection into the muon storage region, the positive muons circulate in a plane parallel to the magnetic field with a radius of 33 cm. They decay into a positron and two neutrinos with a time-dilated lifetime of 6.6 μs. An array of radial vanes made up of silicon-strip detectors measures decay positron tracks to measure the spin precession of muons.

The anomalous muon precession period is 2.2 μs, which is about 300 times the cyclotron period (7.4 ns), i.e. the muon spin rotates 360 degrees in every 300 turns in the storage region. Because of the parity violation in the weak decay of the muon, higher energy positrons tends to decay in parallel to the direction of muon's spin [17]. In this experiment, the detectors measure positron tracks which have energy above 175 MeV.

Due to the Lorentz boost, the positron direction is confined to a narrow cone parallel to the parent muon direction. The positrons curl into the inner part of the muon storage region where the magnetic field is as strong as that in the muon storage region (3 T). The positron momentum component parallel to the magnetic field causes it to drift vertically. The detector system needs to be large enough to accept positrons which curl to the inside of the muon storage region with a vertical drift. The volume for the detector system is a tube inside the muon storage area with 40 cm in height and 27 cm in radius.

The detectors and their readout electronics must operate under a 3 T magnetic field. Any electric field from the detector and readout electronics should be sufficiently small so that the electric field in the muon storage region is negligible for the measurement. A few mV/m for a ppb systematic uncertainty.

We plan to use a double-sided AC-coupled rectangular silicon-strip sensor with vertical and stereo strips with 200 μm pitch. The size of the sensor is 10 cm wide and 20 cm high. A total of 64 units of silicon strip planes will be radially placed in the detection volume to efficiently detect the circular tracks of the positrons. 32 units are used to form a set of vanes in the upper half of the detection volume, and another 32 units are for the lower half. There are 1500 strips per unit, and 96k strips in total.

2.4 Statistics and required beam time

The statistical sensitivity of the anomalous precession frequency is estimated as

$$\frac{\delta\omega_{\rm a}}{\omega_{\rm a}} \sim \frac{1}{\gamma}\frac{1}{\sqrt{N_{\rm e^+}P_{\mu}^2A^2}}, \quad (4)$$

where $N_{\rm e^+}$, P_μ, and A denote the number of detected positrons from muon decays, muon polarization and the analyzing power, respectively. The analyzing power would depend on the energy cut in the analysis. A 0.1 ppm measurement requires number of detected positron of 1.5×10^{12}. Fig. 2 shows expected positron spectrum for such a case assuming a muon polarization, P_μ of 1.0.

For the minimum polarization of 0.5, the 0.1 ppm statistical sensitivity requires $6\times10^{12}{\rm e}^+$. A measurement of 0.5 ppm sensitivity will be a very significant initial goal, making a strong impact on the physics, since this statistical sensitivity is identical to the previous measurement, E821. This step requires $6\times10^{10}{\rm e}^+$, corresponding to about a month of running with a muon polarization of 0.5.

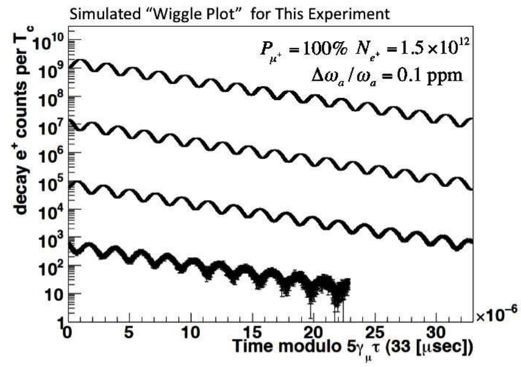

Fig. 2. Expected time-dependent positron yield from the proposed experiment

The physics production run should be divided into a few phases at least; the first step would be to reach the precision of the E821, and then further improvements would follow.

3 Summary

We propose to measure the anomalous magnetic moment of the positive muon a_μ down to the level of 0.1 ppm with a novel technique utilizing an ultra-cold muon beam accelerated to 320 MeV and a 66 cm diameter precision magnetic storage ring without introducing electric field for focusing. The beam will be also useful in measuring the electric dipole moment beyond current precision.

The proposed measurement will provide a rigorous test of the Standard Model of particle physics as demonstrated by previous experiments. Our measurement will be complimentary to the previous measurement which was done at 3.1 GeV, the "magic" energy approach with a 14 m diameter storage ring. This proposed experiment will have different systematics from the previous experiment.

An experimental proposal was submitted to the J-PARC PAC in 2009 [18] and discussed in the PAC meeting in January, 2010.

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