New approach to the Muon g-2 and EDM experiment at J-PARC

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Abstract. A new measurement of anomalous magnetic moment of the positive muon a_μ down to the level of 0.01 ppm and the electric dipole moment EDM with the improved sensitivity better than order of magnitude is proposed. Novel techniques utilizing an *ultra-cold muon beam* accelerated to 300 MeV/c and a 66 cm diameter of super-precisely controlled magnetic storage ring are introduced. An unique beam injection and storage scheme to control the beam trajectory into such a compact storage ring are also discussed.

1. Introduction

The anomalous magnetic moment of the muon a_μ is directly sensitive to the electromagnetic, strong, and weak forces and has been calculated from know physics, referred as the Standard Model (SM):$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Had}} + a_\mu^{\mathrm{EW}}$. a_μ has been measured for more than half a century at CERN and BNL. The present best experimental value from a_μ is from the E821 experiment at BNL, which achieved a sensitivity of 0.54 ppm [1]. This measured value, a_μ^{exp} = 116 592 089(54)(33)$\times 10^{-11}$, and the calculated theoretical value, a_μ^{SM} = 116 591 834(2)(41)(26) $\times 10^{-11}$ [2], differs by more than 3 standard deviations:

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 255\ (63)(49) \times 10^{-11}. \tag{1}$$

In order to conclude that whether this discrepancy is a hint of a *new* physics or not, we need to go one more step further to achieve the super-high precise knowledge from both experiment and theory.

The electric dipole moment of the muon, d_μ, has also been searched for over decades. While a_μ serves as a solid test ground for the Standard Model of a particle physics, a non-zero d_μ value immediately means CP violation in the lepton sector provided CPT theorem holds. The most recent measurement of d_μ (as well as a_μ), E821 at BNL [3], has constrained d_μ down to:

$$d_\mu < 1.8 \times 10^{-19} [\mathrm{e} \cdot \mathrm{cm}]. \tag{2}$$

This is, however, required improvement to compare to a limit from the electron within lepton universality ($d_\mu \leq 10^{-24}$ e·m). Or some Standard Model extensions predict the limit larger than 10^{-23} e·cm.

We are now proposing super-high precise measurements of a_μ and d_μ with a completely independent experimental method, applying leading-edge technologies in the world, at JAPAN Proton Accelerator Research Complex J-PARC.

2. a_μ, d_μ and the muon spin precession

The muon magnetic moment is related to its intrinsic spin by the gyromagnetic ratio g_μ:

$$\vec{\mu}_\mu = g_\mu \left(\frac{e}{2m_\mu}\right) \vec{S}, \tag{3}$$

where m_μ is a mass of muon. In case of a structureless particle $g_\mu = 2$ is expected. Anomalous magnetic moment is defined by $a_\mu \equiv (g_\mu - 2)/2$.

The muon dipole moment is also related to its intrinsic spin and parametrized as:

$$\vec{d}_\mu = \eta \frac{e\hbar}{2m_\mu} \vec{S}. \tag{4}$$

In the presence of the static field $\vec{B}$ and $\vec{E}$, the Hamiltonian of the system can be written as

$$H = -\vec{\mu}_\mu \cdot \vec{B} - \vec{d}_\mu \cdot \vec{E}, \tag{5}$$

here, the second term, $-\vec{d}_\mu \cdot \vec{E}$ is odd under P and T transformations. Therefore a nonzero value of d_μ violates T, and also CP, if CPT theorem holds.

One of the best way to measure a_μ and $d_\mu (\equiv |\vec{d}_\mu|)$ directory by experiment is to measure the muon spin precession in the magnetic field. The precession frequency $\vec{\omega}$ of the moving muon, whose of momentum vector $\vec{\beta}$ in the presence of the static field $\vec{B}$, is expressed as:

$$\vec{\omega} = -\frac{e}{m_\mu} a_\mu \vec{B} - \frac{d_\mu}{\hbar}\left(\vec{\beta} \times \vec{B}\right) \equiv \vec{\omega}_a + \vec{\omega}_d. \tag{6}$$

The first term is a precession frequency come from anomalous magnetic moment. The second term comes from dipole moment if it exists. Note that relativistic particle feels electric field as $\vec{\beta} \times \vec{B} = \vec{E}$. From equation 6, it is clear that the first and the second terms are orthogonal vectors. Therefore we can measure two frequency vectors independently. And I would emphasize that we should be sensitive to two frequency vectors, otherwise we can not achieve super high precise measurement to meet our physics goal. In this article we call the precession frequency from anomalous magnetic moment (the first term) is $\vec{\omega}_a$, and a frequency from the electric dipole moment (the second term) is $\vec{\omega}_d$.

3. Overview of a new experiment

Procedure of this experiment is outlined as follows: (1) storage the muon beam in the uniform magnetic field $\vec{B}$; (2) measure $\vec{\omega}_a$; (3) measure $\vec{\omega}_d$; (4) measure magnetic field $\vec{B}$ along the muon trajectory. From these three measured values, we can extract physics result a_μ and d_μ directly from equation 6.

This simpleness is guaranteed as long as there is **NO** electric field around the muon trajectory ($\leq$ 10mV/m). In the presence of electric field, equation 6 becomes more complicated and $\vec{\omega}_a$ and $\vec{\omega}_d$ are no longer orthogonal. Elimination of the electric field is a biggest technical challenge and difference compared to the previous experiments[E821, CERN], which employed electric focusing field system to control muon beams.

Without electric focusing field, very straight muon beam, whose transverse momentum is small compared to the longitudinal momentum: $p_T/p_L \sim 10^{-5}$ is the key for this experiment. Such an *ultra-cold* beam should be controlled utilizing very weak focusing magnetic field only. Figure 3 displays overview of the beam line of this experiment. I will introduce two major points briefly.

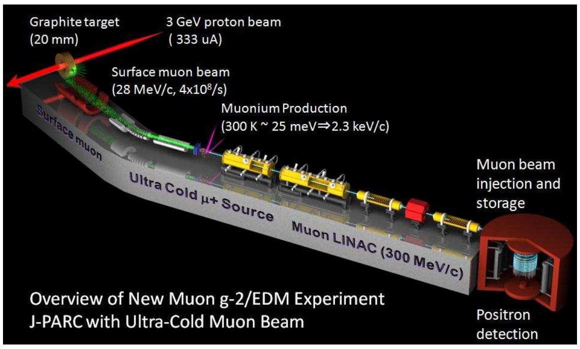

Figure 1. Overview of the J-PARC $g-2$ experiment. All details are discussed in a proposal submitted to J-PARC PAC, 2009.

3.1. *Ultra-cold muon beam production*

Now I would mention briefly how the muon beam is produced as displayed in figure 3 [4]. The 3 GeV proton beam from the J-PARC Rapid Cycle Synchrotron hit the graphite target and produce pions which will stop in the target. Those π^+ that stop on the surface of the target decay to μ^+, which will be collected as surface muon beam and followed to a Mu production target.

The transported surface muons will stop in the Mu production target, and form Mu (muonium:μ^+-e^- atom). The Mu behaves like hydrogen atoms and diffuses from the target and drift with its thermal energy as shown in figure 3.1. We are aiming to operate Mu production at room temperature (300 K). This corresponds to the Muonium kinetic energy of $\sim$ 25 mV, 2.3 keV/c in momentum only! This is why we call *ultra-cold*.

Then the Mu is ionized by pulsed lasers at near the target surface. And finally, we have polarized ultra-cold muons. The muons are then accelerated by LINAC up to $P_L = 300$ MeV/c, without changing its transverse momentum dispersion ($P_T \sim 2.3$keV/c). In this way, we have very straight ultra-cold muon beam: $p_T/p_L \sim 10^{-5}$.

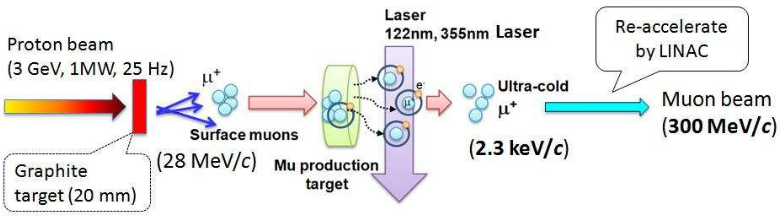

Figure 2. Ultra-cold muon generation. Details are discussed in text and reference [4].

3.2. *Muon precession measurement in the storage ring*

The ultra-cold muon beam is injected into the storage ring along 3-dimensional *spiral trajectory* as displayed in left side of figure 3.2. Storage magnetic field is 3 Tesla. The cyclotron radius and period are 33.3 cm and 7.4 nsec respectively. This beam injection scheme is a quite unique. I will discuss about this topic in Section 4.

Stored muon will decay into a positron, a neutrino and an anti-neutrino: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$. Parity non-conservation in the weak decay and helicity conservation lead to an asymmetry in the angular distribution of the decay positrons with respect to the direction of the muon spin. Viewing the decay in the muon rest frame, decay positron has its maximum momentum and is 100 % polarized when the two neutrinos are emitted to the opposite direction of the positron. Therefore, event rate of *boosted* higher energy positrons in the rest frame changes periodically in synchronization with the muon precession frequency. Left side of figure 4 displays an expected positron time spectrum applying proper energy threshold simulated by use of GEANT4. Interval

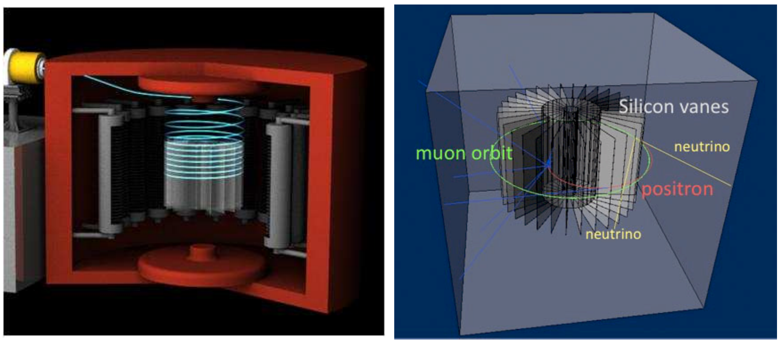

Figure 3. Left: storage ring and 3-dimensional spiral injection.
Right: Silicon tracker for positron detection.

between the peaks correspond to the muon precession period as shown in equation 6. We expect the ultra-cold muon beam of order of 10^6 per second from the source. This is enough statistics to achieve 0.1 ppm in a year (10^7 seconds)!

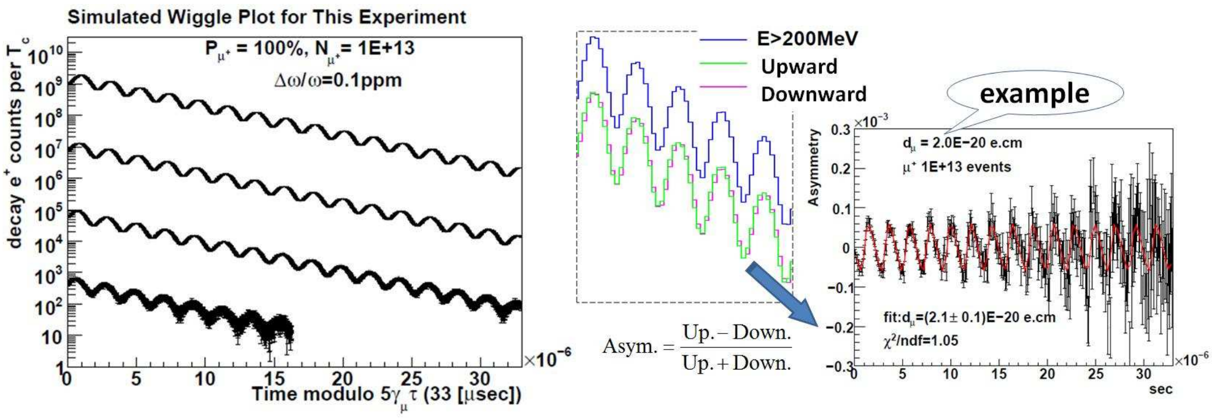

Figure 4. Left: Positron time spectrum above appropriate energy threshold. Right:Blue solid line is the same spectrum as shown in right plot. Green and pink lines are subset spectra of **upward** and **downward** positrons. Rightest plot is asymmetry between them.

We need one more step to decompose $\vec{\omega}_a$ and $\vec{\omega}_d$ from $\vec{\omega}$. As discussed in equation 6, $\vec{\omega}_d$ is parallel to the outer product of $\vec{\beta} \times \vec{B}$, i.e., $\vec{\omega}_d$ stays always on the muon orbit plane. This makes phase difference between two positron spectra emitted to **upward** and **downward** the muon orbit plane as shown in right side of figure 4. Therefore, if we take asymmetry of these two spectra, we can extract ω_d. We expect the sensitivity is $d_\mu \sim 10^{-20}$e·cm or better. Biggest source of the systematic uncertainty, however, is how well we control and know the muon orbit plane precisely. This is closely related with the muon beam injection scheme, which is discuss in the next.

4. Beam Injection and Storage

One of new interesting technical challenges is the muon beam injection into storage ring. Higher magnetic field (i.e. higher precession frequency: see equation 6) and higher momentum of muon beam (i.e. longer lifetime) are of advantage for the precise ω measurement. Based on current technical capabilities and estimation cost, we design 3 Tesla of the storage magnetic field and 300 MeV/c of the muon beam. This corresponds to the cyclotron radius of 0.33 m and period of 7.4 nsec. Such a *compact* storage ring requires brand-new beam injection concept: **3-dimensional spiral injection scheme**.

Left plot of figure 5 displays a conceptual design of upper half cross-section view of the storage ring magnet and a single muon injection trajectory. This simulation is done by use of OPERA 3-D. This magnet consists of superconductive solenoidal main coil, cylindrical iron poles, return yoke and iron end plates. The storage region is defined on the mid-plane, with a radius of 33.3 ± 3.0 cm and height of ± 10 cm. Dedicated study to control super-precise field is ongoing [5].

An unique point of this scheme is utilizing a fringe field to steer the beam to the storage field volume. A solenoidal magnet is suitable to realize such injection scheme. As shown in left side of figure 5, the beam will enter the solenoid through a hole in the iron end plate. In the fringe region, beam momentum is deflected vertically by a radial magnetic field B_R as shown in right side of figure 5. Careful design of the radial field in the fringe region provides ideal deflection on entry angle (with regards to the ideal orbit plane) from $\pi/4$ radian to 5 mrad. Only a small vertical momentum remains when spiraling beam reached the beginning of the storage region.

The beam will then spiral through the field storage region and a magnetic kicker will deflect the beam to stop the vertical motion and guide to a stable orbit at the center of the storage region. The duration of the kick can be for a several tens of cyclotron (or revolution) periods ($\sim$ 100 nsec), science a longer kicker pulse allows a low kicker field and more stability. Stability of vertical kick is expected to be better than 0.1% and residual entry angle is order of μ rad. Such beam can be trapped perfectly by weak magnetic focus field ($\leq 10^{-6}$ Tesla) inside the storage volume. Outline cartoon of this injection scheme is displayed in right plot of figure 5. Beam dynamics study is ongoing to estimate requirements of beam acceptance for this injection scheme as the next step. We are also planing a verification test of this scheme by use of electron beam and prototype solenoid magnet.

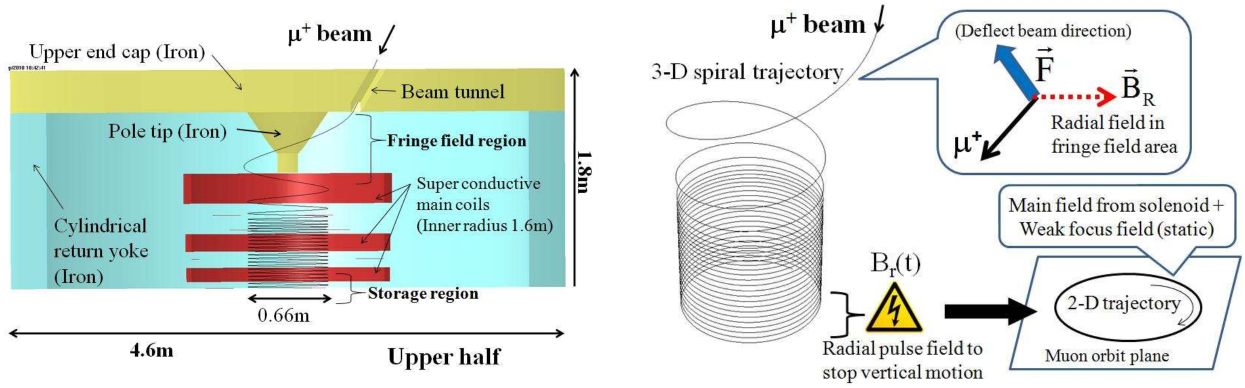

Figure 5. Left: Conceptual design of upper half cross-section view of the storage magnet. A single muon trajectory is also shown. Right: Outline of 3-D spiral injection scheme.

References

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