A New Experiment for an Electric Dipole Moment of Muon at the $10^{-24}\,\mathrm{e\,cm}$ level.*

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Abstract

We propose using the existing g-2 ring to search for an electric dipole moment of the muon with a dedicated experiment. We are confident that we can improve by six orders of magnitude the current sensitivity to the muon EDM, both in statistics and systematics, bringing it down to $10^{-24}\,\mathrm{e\,cm}$. We will be sensitive to several non-standard models of CP violation at this sensitivity and will be competitive to the electron EDM experiments for the first time. A lower energy muon beam, strong magnetic focusing, lithium lens target with modified beam transport and inflector system, placing the detectors above and below the vacuum chamber, and applying a flat radial electric field to cancel the $g-2$ precession, maximize the sensitivity of the proposed experiment to the muon EDM.

1 Introduction

We propose to search for an electric dipole moment (EDM) of the muon using the existing muon g - 2 ring. [2] The large number of polarized muons necessary for achieving a small statistical error is only possible due to the high intensity primary proton beam available at the AGS. The EDM value expected from the Standard Model is negligibly small, [3] about $10^{-35}\,\mathrm{e\,cm}$ which makes the search of the muon EDM a powerful probe for new physics.

The present experimental limit [4] is $1.05 \times 10^{-18}\,\mathrm{e\,cm}$ (95% c.l.). Super Symmetric (SUSY) models, [5] two and multi-Higgs doublet models predict much larger values from contributions involving Higgs boson exchange. [6, 7] The predicted value for the electron EDM is in the neighborhood of its present experimental limit and for the muon (scaling linearly by the ratio of the masses) near the experimental accuracy claimed in the present paper. Other, less generic models, predict even larger values, [5] as large [8] as $10^{-21}\,\mathrm{e\,cm}$. Also, left-right symmetric models predict [8, 9] values in the range of low $10^{-23}\,\mathrm{e\,cm}$.

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The electric dipole moment upper limits for the electron [10, 11], $d_e = (1.8 \pm 1.2 \pm 1.0) \times 10^{-27}\,\mathrm{e\,cm}$ and for the neutron [12] $d_n = (-30 \pm 50) \times 10^{-27}\,\mathrm{e\,cm}$ have already been used to set limits on SUSY models. [13, 14] Even if experimental evidence for an EDM in the electron and/or the neutron existed, the prospects of having available another system where the models could be checked would be very valuable. [8] Since we do not know the mechanism by which electrons and muons might acquire an EDM, it is important to improve the EDM limits of both particles. [15] In various models, the EDM value goes as the second or third power of the ratio of the muon mass to that of the electron mass as, for example, is the case with various multi-Higgs models. [16]

The muon g-2 experiment underway at BNL will probe a wide range of non-standard physics, in particular SUSY models [17, 18, 19] with large $\tan\beta$ (≥ 10). The muon EDM experiment is also sensitive to some of those models and together they explore a larger parameter range. [20]

2 Experimental Overview

The muon spin precession angular frequency (relative to the momentum vector) in the presence of both electric and magnetic fields is given by

$$\begin{aligned}\vec{\omega} &= -\frac{e}{m}\{a\vec{B} - \frac{a\gamma}{1+\gamma}(\vec{\beta}\cdot\vec{B})\vec{\beta} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \\ &\quad \frac{\eta}{2}[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}] - \frac{\eta\gamma}{2(\gamma+1)c}(\vec{\beta}\cdot\vec{E})\vec{\beta}\}, \end{aligned} \tag{1}$$

where $a = (g-2)/2$ and η is the EDM in units of $\frac{e\hbar}{4mc}$. This simplifies to

$$\vec{\omega} = -\frac{e}{m}\{a\vec{B} + (\frac{1}{\gamma^2-1} - a)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\}, \tag{2}$$

using the fact that $|E| << |B|$ and assuming the muon velocity is orthogonal to the external magnetic field ($\vec{\beta}\cdot\vec{B} = 0$). η plays a role for the EDM corresponding to the g factor for the magnetic dipole moment. The muon EDM couples to the external magnetic field because in the muon rest frame it looks like an electric field due to the Lorentz transformation. The EDM value in MKS units is given by

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2mc} \simeq \eta \times 4.7 \times 10^{-14}\,\mathrm{e\,cm}. \tag{3}$$

From the above equation (2) is apparent why the present $g-2$ experiment uses muons at the "magic" γ, i.e. $\gamma = 29.3$ since at this value the coefficient $\frac{1}{\gamma^2-1} - a = 0$ and the muon spin precession becomes independent of the electric field present in the lab frame. For the dedicated EDM experiment we propose to use muons with much lower energy so that the radial electric field cancels the $g-2$ precession leaving the EDM precession to operate on its own and accumulate over many microseconds. The required electric field is

$$E = \frac{aBc(\gamma^2 - 1)}{\beta} = 2\,\mathrm{MV/m}, \tag{4}$$

for $\gamma = 5$, $B = 0.24\,\mathrm{T}$ and a magnet radius of 711 cm. Two parallel plates 10 cm apart with ± 100 KV voltage can create such a field.

We are currently investigating the possibility not to use any electric fields to cancel the g-2 precession since it requires a feedback system to keep the average vertical E-field below 10 nrad (see later section on electrode alignment). This way we will also be able to store many more muons since higher momentum muons may be used. However, in this letter we will only assume the case where the flat radial field is used.

2.1 Target and Beam Line

In order to obtain sufficient muon storage at a momentum of 0.5 GeV/c, it will be necessary to increase the acceptance of both the beam transport and the storage ring. A strong focusing upgrade of the g-2 ring would require replacement of the present pole face of the magnet with 36 alternating gradient poles to give a $\beta^x_{max} = 4.5$ m, $\beta^y_{max} = 4.3$ m and a momentum acceptance of $\pm 3\%$.

A 10 cm diameter by 25 cm lithium lens pulsed at 800 KA with a gradient of 3.2T/cm located 20 cm, center to center behind the production target would capture 0.9 GeV/c secondary pions beyond the maximum production angle of 8-10 degrees indicated in the Sanford-Wang [22] parameterization.

Simulations using the Sanford-Wang parameterization of particle production indicate 8.6×10^5 stored muons per bunch of 10^{12} protons on target is a realizable goal (assuming the inflector has 100% injection efficiency) at the present AGS intensity, and 13.4 GeV/c proton beam.

An increase in the proton current by a factor of 2.5 by the year 2000 is anticipated bringing up the proton beam intensity to 100 TP. The estimated number of stored muons will be 8.6×10^7 every 1.25 seconds. In 6000 hours it would be possible to accumulate 1.5×10^{15} stored muons. We are investigating the possibility to use a smaller diameter lithium lens by a factor of 3 to further increase the number of captured pions and reduce the required total running time.

2.2 Inflector and Storage Ring

The injection of beam into the storage ring is usually done with a septum magnet (inflector), which locally cancels the field of the main magnet, so that the beam enters the storage region nearly tangential to the equilibrium orbit.

A direct current non-ferrous superconducting inflector has been designed and constructed for E821 (muon g-2) experiment. [23] In the EDM experiment the leakage field requirement is much more relaxed and simpler designs are acceptable. We are planning to use a water cooled normal conductor. The influence of the inflector at the muon storage area can be reduced by shimming it to the required accuracy.

Since the search for an EDM does not require an accurately known magnetic field, the use of strong magnetic focusing is very advantageous. We plan to use the 36 pole pieces on top and 36 on bottom shaped in such a way that they provide $\frac{\partial B}{\partial R} = 1.45$ T/m of 36 alternating gradient focusing regions. The main dipole field (for the 0.5 GeV/c muon momentum case) is 0.24 T and therefore the regional field focusing index is $n = 43$. The phase advancement is 44.5° per region. Assuming the same muon storage region of 9 cm in diameter, as in the current g-2 experiment, the estimated beta functions are $\beta^x_{max} = 4.5$ m, $\beta^y_{max} = 4.3$ m. The compactification factor is 5.9 giving an overall factor of 50 improvement in the number of stored muons over a comparable system with an electrostatic weak focusing. We are also considering a redesign of the beam storage vacuum chamber to optimize it for the EDM experiment.

There is a need to have a kicker in order to be able to inject muons into the ring. One third in length of the current kicker used in g-2 with two thirds the peak current would suffice. The eddy currents of this kicker would be sufficiently low not to become a source of systematic errors.

2.3 Electrode alignment

The vertical component of the electrostatic field in the muon storage region, averaged over the ring circumference, must be well suppressed. An average component of 10 nrad will induce an effect mimicking an EDM of $10^{-24}\,$e cm. This implies that the electrodes, and the top and bottom plates used to produce a uniform electrostatic field, must be aligned with respect to the horizontal plane with high precision.

Fig. 1 shows a method that may be used to achieve this alignment. The electrodes and top and bottom plates are clamped at intervals with pairs of U-shaped machinable ceramic yokes. The top and bottom plates are made of glass doped to produce a small but uniform conductivity bonded to insulating webbing for support. The outer surfaces of the conductive glass are covered with an antireflection coating so that the parallelism of the inner surfaces of the top and bottom plates may be tested, after clamping, by optical interferometry. Shimming may be necessary to insure that these inner surfaces are parallel.

The conductive glass plates are then referenced to a water surface in hydrostatic equilibrium by means of precision glass rods with lengths that have been tested by optical interferometry. The upper ends of these rods support the lower conductive glass plate. The lower ends are metallized, and are brought within 1 mm of the water surface. The capacitance between each rod and the water surface is monitored, and the position of each rod adjusted continuously by a servo loop to maintain a fixed gap between the rod and the hydrostatic surface. The rods are clamped to a lever driven by a pair of piezoelectric transducers, which are in turn supported by a support beam which runs around the periphery of the magnet. These leveling devices would be positioned at 0.5 to 1 m intervals around the circumference of the ring.

A similar hydrostatic leveling scheme has been used to align magnets in the European Synchrotron Radiation Facility (ESRF) [26]. This system has an analog resolution of better than 2 μm and a digital resolution of better than 0.1 μm, and is used to align the ESRF magnets over its 1 km circumference. If we decrease the gap between the rod and water surface to less than 1 mm from the 6 to 8.5 mm used at the ESRF, the analog resolution will be decreased to 0.3 μm. Further improvements may be obtained by using low-noise front ends and signal averaging, so that the alignment precision will be determined by the precision of the interferometric parallelism measurement ($\pm 0.2\mu$m) and thermal expansion (0.03 μm for a 0.1°C temperature differential). The local angular error will be approximately $\pm 0.1\mu$rad. The angular error, averaged over the ring, will be significantly smaller if the local errors are uncorrelated, i.e. $\pm 0.01\mu$ rad .

Since the required magnetic field is one sixth of the one currently used, we can open up the magnet gap further and increase the available space for the leveling feedback server. We need to make a prototype and find out the limitations of this technique.

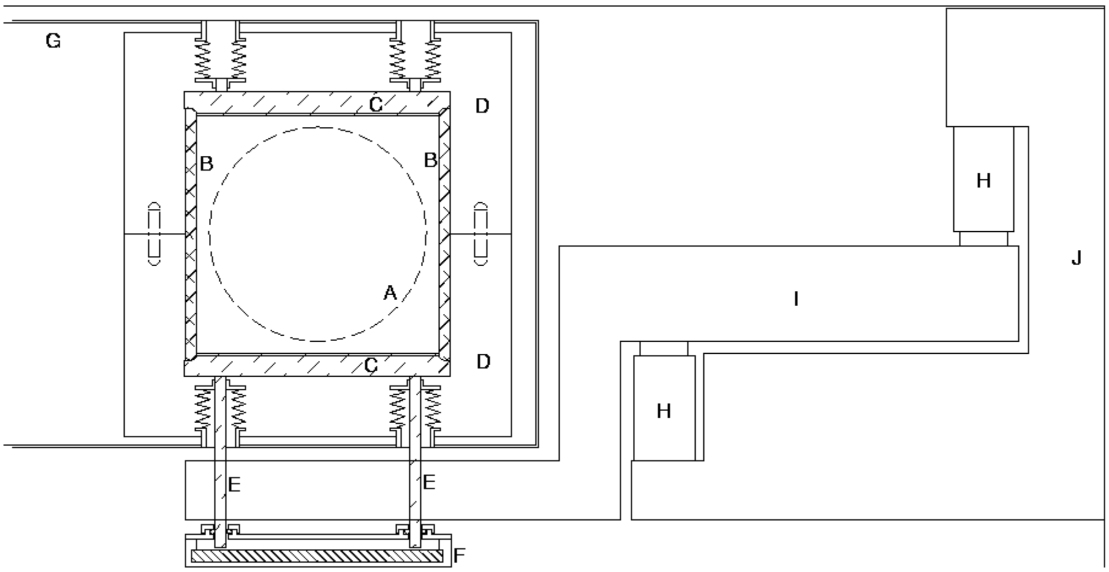

Figure 1: Scheme of electrode alignment showing: (A) muon storage region; (B) electrodes; (C) conductive glass plates with insulating support webbing; (D) ceramic alignment yokes; (E) glass reference rods; (F) hydrostatic reference surface; (G) vacuum chamber; (H) piezo-electric driver; (I) lever; and (J) support beam.

2.4 Detectors

The lower momentum decay electrons need thinner calorimeters than the present ones used for the g-2 experiment. [2] Those can be placed on the top and bottom of the vacuum chamber extending inwards, towards the center of the ring to cover as much solid angle as possible. The location of the detectors is driven by the desire to maximize both acceptance and the asymmetry of the decay electrons. The total acceptance of the detectors corresponds to approximately 65% of the stored muons when only top/bottom detectors are used. [27] The average asymmetry value is 0.3 which can be increased by using the number of electrons separately in (for e.g.) five energy bins. We are also considering the use of detectors on the inner side of the storage ring.

We think it is advantageous to look at the total charge collected by the detectors rather than at individual pulses, the method known as the "Q" method [28].

3 Sensitivity Level

The EDM sensitivity is given by (in MKS units)

$$\eta = \frac{2\theta_t}{\beta B t}\frac{m}{e}, \tag{5}$$

with θ_t the minimum transverse spin precession angle which can be detected, m, e the muon mass and charge respectively, and B, the average magnetic field seen by the muon. The uncertainty in η is

$$\sigma_\eta = \frac{1}{\gamma\tau_0 A_1 A\sqrt{2N_{Tot}}}, \tag{6}$$

with $A_1 = \beta e B/2m = 10^8$/s for $B = 0.24$T, N_{Tot} the total number of observed decays, τ_0 the muon lifetime at rest, γ the Lorentz boost factor, and A the asymmetry. If one observes 1.5×10^{15} decay electrons which have an average transverse asymmetry of 0.3 then the uncertainty in η is 5.5×10^{-11}, and on the EDM $2.5 \times 10^{-24}\,$e cm. In two muon lifetimes (i.e. $2 \times 11\mu$s) this corresponds to a vertical precession angle of 120 nrad.

The sensitivity of the experiment increases as the B field and the lifetime increase. However, the necessary electric field which is canceling the muon $g-2$ spin precession also grows fast as can be seen by equation (4).

3.1 Systematic Errors

Potential systematic errors include the following:

1. Early to late electron counting due to rate effects. With almost 10^8 muons entering the ring and a good fraction of them decaying within $10\,\mu s$ the rates are very high. Our detector will be scintillating fiber calorimeters with photodiode readout. The readout electronics are specially made so that they maintain their linearity to 10^{-4}. [29] With 400 such systems the error is further reduced another factor of 20. We will be interchanging electronically the top/bottom detector readout randomly about 10000 times which brings us to 5×10^{-8} linearity error.

2. Proton or pion contamination of the muon beam. During the 1997 run of the g-2 experiment where there were injected about 10^8 pions per spill, the pion flash was the biggest problem. After striking a nucleus they produce secondary neutrons which in turn produce gammas paralyzing the photomultipliers mostly at the first half of the ring for tens of μs. When we tried the muon injection by lowering the accepted particle momentum by about 1.5% the light flash went down by a factor of 50.

In the muon EDM experiment the secondary beam is 900 MeV/c whereas the muons have half that. One can expect a proton/pion leakage of less than 10^{-4} per muon. If we assume that the lower momentum particles are less likely to produce a neutron by a factor of 2 and taking into account that most of the injected particles (i.e. 90%) are expected to be stored and not get lost, the total particle population in the ring producing a neutron will be 5×10^9 for a total of 1.5×10^{15} stored muons. Assuming that they cause a 0.5% asymmetry on top versus the bottom detectors (in the worse case) the effect will be below the sensitivity of the experiment.

3. Due to the cylindrical nature of the electrostatic plates which provide the radial electric field, the E-field decreases as $1/R$ making the cancellation of the g-2 non-perfect as a function of the muon momentum. Also, taking into account that the spin precession cancellation depends on both the magnetic field and the value of gamma (see equation (4)), one can estimate that at the edge of the aperture, the muons will flip the spin horizontally in $100\,\mu$s. Only a very small fraction of the muons will do that. We are investigating the requirement on the acceptance and detector efficiency uniformity so that this effect is also negligible.

4. The problem with radial magnetic fields present, when electrostatic focusing is used, is eliminated completely because we only use strong magnetic focusing.

We feel confident that we can analyze all sources of systematic errors and greatly reduce them due to the flexibility provided by a dedicated muon EDM experiment.

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