Request for R&D Funds Towards a Proposal for the Muon Electric Dipole Moment Experiment

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Abstract

We are requesting R&D funds to develop reliable methods for sustaining high electric field strengths required to cancel the g-2 spin precession and in parallel to develop a deuteron polarimeter. Deuterons could be used to check systematic errors in a muon EDM experiment. These studies will enable us to define a detailed proposal for measuring the muon EDM.

Contents

1 Introduction

Since the LOI of the muon EDM [1] in which we argued for a staged approach towards a sensitivity of $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$ there have been several important developments:

1. Developments in the theory relating to the EDM highlighting the need to probe the second generation for leptonic CP violation.

2. Motivated by the accelerator R&D, new techniques have been developed to sustain much greater electric field strengths than the 2 MV/m we had assumed for the LOI. This prospect is very exciting since it raises the possibility of a much better muon EDM experiment.

3. The E821 announcement of a precision measurement of the anomalous magnetic moment of the muon from the 1999 data analysis.

In view of the above mentioned developments we believe the theoretical and experimental cases for a sensitive search for a muon EDM are very strong. We are currently studying various ring configurations which minimize the systematic errors. The availability of much higher electric fields could lead to a more compact and more sensitive experiment. We are specifically requesting funds for developing high electric fields in the configuration required for the storage ring and to develop a special deuteron polarimeter to monitor the flatness (see below) of that field. This R&D is necessary to formulate the final configuration of the experiment which will allow a proposal to be submitted for FY03.

2 Update of the Theoretical Motivation

The Standard Model of particle physics provides an extremely successful theoretical framework for describing all known particles and their interactions. Even recent observations of neutrino oscillations can be accommodated with small modifications. However, the Standard Model also leaves many fundamental questions unanswered. Among the least understood phenomena is CP violation. At present, the only known source of CP violation in the Standard Model is the phase of the CKM matrix. Its fundamental origins are unknown. Further, while CP violation is an essential ingredient of almost all attempts to

	Present Limit	SM Prediction	$(m_f/m_e) \cdot d_e$ Bound
e	$1.8\ (1.2)\ (1.0) \cdot 10^{-27}$ [12]	$\lesssim 10^{-38}$	—
μ	$< 1.05 \cdot 10^{-18}$ [13]	$\lesssim 10^{-35}$	$< 10^{-24}$
τ	$< 3.1 \cdot 10^{-16}$ [14]	$\lesssim 10^{-34}$	$< 2 \cdot 10^{-23}$
p	$-3.7\ (6.3) \cdot 10^{-23}$ [15]	$\lesssim 10^{-31}$	—
n	$< 6.3 \cdot 10^{-26}$ [16]	$\lesssim 10^{-31}$	—

Table 1: EDM bounds and predictions (in $e \cdot$ cm). Upper limits are 95% C.L. bounds on absolute values. For the electron, the first error is statistical, the second systematic. Assuming linear scaling with lepton mass, the implications of the d_e bound for other lepton EDMs are given in the last column. This is conservative, in many models the scaling is more rapid than linear (see text).

explain the matter-antimatter asymmetry of the universe [2],[1] the amount of CP violation present in the CKM matrix is insufficient to explain the observed asymmetry [4, 5, 6, 7]. Searches for CP violation beyond the CKM matrix are necessary to shed light on this puzzle and are also probes of physics beyond the Standard Model.

Electric dipole moments (EDMs) violate both parity (P) and time reversal (T) invariance. If CPT is assumed to be a valid unbroken symmetry, a permanent EDM is, then, a signature of CP violation [8, 9]. A permanent EDM has not been measured for any of the known elementary particles. In the Standard Model, EDMs are generated only at the multi-loop level and are predicted to be many orders of magnitude below the sensitivity of foreseeable experiments [10, 11] (see Table 1). A non-vanishing EDM measurement would therefore be unambiguous evidence for CP violation beyond the CKM matrix, and searches for permanent EDMs of fundamental particles are powerful probes of extensions of the Standard Model.

Searches for EDMs have been performed for electrons, muons, taus, protons, and neutrons. The current experimental limits are listed in Table 1. The experimental techniques include beams of neutral atoms, molecular beams, stored neutrons and stored charged particles. In heavy atoms and particularly in polar molecules there are substantial enhancement factors due to the utilization of the rather strong internal electric fields within these systems [17]. These limits, particularly for the electron and neutron, have had important implications for theoretical particle physics over many decades [18], and the current

[1] Alternative explanations are subject to stringent bounds. See, e.g., Ref. [3].

bounds are among the strongest constraints on many speculative models. For example, in supersymmetry, they already disfavor models with CP violating phases of order unity, and they have motivated models with $\mathcal{O}(\alpha/\pi)$ phases [19, 20] or heavy superpartners [21].

The muon provides the only possibility for an extremely precise EDM measurement outside the first generation. The potential of this opportunity is further heightened by recent results from the muon g-2 experiment [22]. While the reported deviation in the muon's $g-2$ could be due to the existence of a large muon electric dipole moment d_μ [25] (see below), there are no theoretical models which give such a large effect.

The muon g-2 and the new EDM experiment are complementary in that the magnetic moment anomaly (MDM) and the EDM are related to each other as real and imaginary parts of the same physical quantity [23, 24, 25]. The electric d_μ and magnetic a_μ dipole moments of the muon are defined through

$$\begin{aligned} \mathcal{L}_{\mathrm{EDM}} &= -\frac{i}{2} d_\mu \, \bar{\mu}\sigma^{mn}\gamma_5\mu \, F_{mn} && (1) \\ \mathcal{L}_{\mathrm{MDM}} &= a_\mu \frac{e}{4m_\mu} \, \bar{\mu}\sigma^{mn}\mu \, F_{mn} \ , && (2) \end{aligned}$$

where $\sigma^{mn} = \frac{i}{2}[\gamma^m, \gamma^n]$ and F is the electromagnetic field strength. New physics contributions to Eqs. (1) and (2) (d_μ^{NP} and a_μ^{NP}, respectively) are expected to be closely related. In the absence of all other considerations, one would expect that their coefficients are of the same order, and this experiment will measure their relative phase ϕ_{CP}. The current constraint on a_μ^{NP} from E821 already implies a relation between ϕ_{CP} and d_μ^{NP}, which is shown in Fig. 1 [25]. For "natural" values of $\phi_{\mathrm{CP}} \sim 1$, d_μ^{NP} is of order 10^{-22} e $\cdot$ cm. With the proposed d_μ^{NP} sensitivity of 10^{-24} e $\cdot$ cm, all of the 2σ allowed region with $\phi_{\mathrm{CP}} > 10^{-2}$ yields an observable signal.

Within specific models, predictions for the muon EDM vary widely. As EDMs violate chiral symmetry, the simplest ansatz for EDMs is that they are proportional to fermion masses. Under this assumption, for a sensitivity at the level of 10^{-24} e $\cdot$ cm, the proposed muon experiment is comparable with present limits on the electron EDM.

In many models, however, the scaling is more rapid than linear [9, 26], or the muon EDM may be enhanced by other effects [25]. In particular, there are several well-motivated extensions of the Standard Model, in which the new physics contribution to the muon EDM could be detected by this experiment. These include:

- Supersymmetry with large $\tan\beta$ [27, 28, 29]. The supersymmetric contributions to

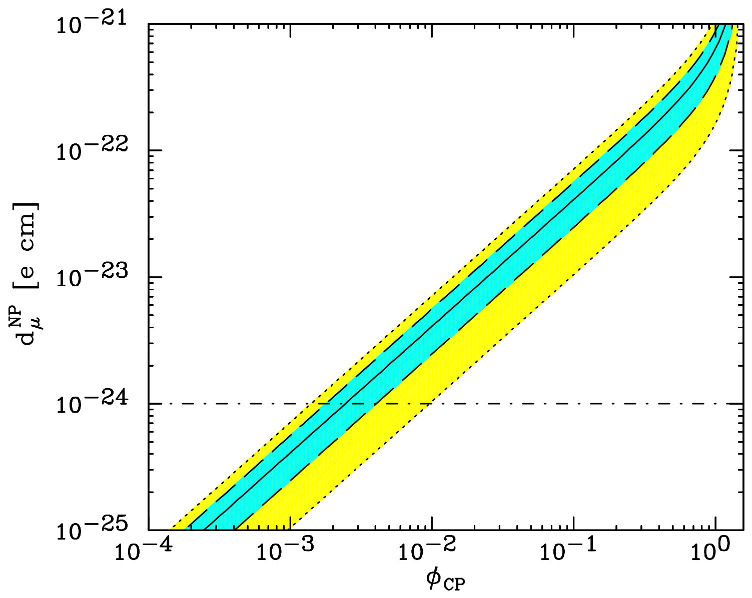

Figure 1: Regions of the $(\phi_{\rm CP}, d_\mu^{\rm NP})$ plane allowed by the current E821 data at the 1σ and 2σ level [25]. The horizontal line shows the targeted sensitivity to $d_\mu^{\rm NP}$ of this experiment.

EDMs and MDMs of the charged leptons are enhanced by the parameter $\tan\beta$, which is the ratio of the vacuum expectation values of the Higgs fields. In $SO(10)$ grand unified theories, $\tan\beta$ is expected to be rather large, of the order of 50. In the simplest models the dipole moments scale linearly with the lepton mass. However, the scaling relation is violated in models with slepton mass nonuniversality [25] or non-proportionality of the A-terms [30]. In those cases the prediction for $d_\mu^{\rm NP}$ is further enhanced by up to an order of magnitude.

- Realistic supersymmetric models of flavor will generally have both lepton flavor violation and CP violation, and may predict $d_\mu^{\rm NP} \sim 10^{-22}$ e $\cdot$ cm [25].
- In left-right supersymmetric models [31] d_μ could be as large as $\sim 10^{-23}$ e $\cdot$ cm, while generic left-right models may even allow values up to 10^{-21} e $\cdot$ cm [32].
- Two Higgs doublet models [33, 34, 35].
- Multi Higgs scenarios [32, 36].

Note that all these theoretical ideas also strongly motivate sensitive searches for forbidden decays, e.g. the lepton number violating muon electron conversion [37], the decay $\mu \to e\gamma$ [38] and precise measurements of particle characteristics such as the muon magnetic anomaly [39].

The wide interest in the muon EDM was highlighted during the well-attended EDM workshop held at BNL in May 2001 [40], when many of the above theoretical issues were discussed and the importance of the muon EDM was emphasized.

3 Experimental Approach

We propose to mount an R&D program in order to optimize the electric field value and configuration for our proposed EDM experiment along with a deuteron polarimeter in order to monitor this electric field. The experimental considerations are briefly outlined below.

In the presence of $\vec{E}$ and $\vec{B}$ fields, in the approximation that $\vec{\beta}$ is perpendicular to $\vec{E}$ and $\vec{B}$, the spin precesses according to

$$\vec{\omega} = -\frac{e}{m}[a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c})], \tag{3}$$

Here a_μ is the magnetic anomaly and η is proportional to the EDM,

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2m_\mu}$$

First, let us discuss the EDM in relation to the currently running muon g-2 Experiment, E821. The first two terms give the precession, ω_a, due to the magnetic moment. For the measurement of the magnetic moment anomaly, E821 uses a very homogeneous vertical $\vec{B}$-field with a quadrupole $\vec{E}$-field for focusing. The effect of the $\vec{E}$ field in the second term on ω is minimized by operating at the "magic" $\gamma \approx 29.3$, where the coefficient of that term is zero. Then $\vec{\omega}_a$ is parallel to the vertical B-field, proportional to both B and a_μ and independent of the electric field. The third term is the precession, ω_η, due to the EDM. Note that the radially directed term $\vec{\beta} \times \vec{B}$ (the "motional" electric field) is far larger than $\vec{E}$, and $\vec{\omega}_\eta$ is therefore directed radially.

The presence of an EDM causes the total precession vector $\omega = \omega_a \sqrt{1 + (\frac{\eta\beta}{2a})^2}$ to tip radially from the vertical direction, by the angle $\tan\delta = \frac{\omega_\eta}{\omega_a} = \frac{\eta\beta}{2a}$. The average directions of the spins then no longer precess in a horizontal plane, but in a plane which is tipped. The spin directions bob above and below the horizontal plane at frequency ω. By observing the amplitude of the consequent up and down motion of decay positrons, one can measure (or place a limit on) the EDM. The CERN g-2 experiment in the 1970's used this approach to get the current limits on the muon EDM: $3.7 \pm 3.4 \times 10^{-19}\,\mathrm{e \cdot cm}$.

The corresponding analysis is under way by E821, which expects to improve on the CERN error by a factor of about 5. In the (unlikely) event that all of the difference between the recent E821 magnetic anomaly measurement [22] and the standard model prediction, $\Delta a_\mu = 43(16) \times 10^{-11}$ is due to the presence of an EDM, one obtains a value for the EDM of $3.0 \pm 0.6 \times 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$. However, there are no theoretical models which could accommodate such a large muon EDM.

A new approach is being proposed for a dedicated measurement of the muon EDM. The tilt of the precession plane to be measured in E821 is extremely small (~ 0.5 mrad), making a precision measurement of the EDM better by this method very difficult. We are proposing a new approach where we cancel the precession of the spin in the horizontal plane (due to MDM) by applying a radial E-field so that the first two terms in equation (3) cancel, giving $\omega_a = 0$. The only remaining precession is then that due to the EDM in the third term, ω_η, with the result that the vertical movement of the spin due to the EDM accumulates over time.

Of course, such an approach is not possible at the magic momentum, since the coefficient of the second term in equation (3) is zero. We must go to a lower muon momentum. In our original letter of intent, we took a conservative value of 2 MV/m for the maximum applied E-field, which led to a B-field of 0.23 T corresponding to 500 MeV/c muons stored at the radius of 7 m in the current g-2 ring. Thanks to substantial recent developments in the maximum possible E-fields from accelerator R&D, we anticipate that this limit can be increased dramatically [41]. This could allow us to go to higher muon momenta, where the sensitivity to the EDM is larger, see Figure (2).

In Figure (2) (top left) we show the sensitivity factor versus the muon momentum when there is an electric field cancelling the g-2 precession (the sensitivity is taken as equal to 1 at 500 MeV/c). For this plot the ring radius was taken as 7.11 m, i.e. the same as in the muon g-2 ring. The sensitivity to the muon EDM increases by about an order of magnitude going from 500 to 1600 MeV/c and this is only possible if higher electric fields are feasible.

A significant potential source of systematic error, which is an important consideration in the design of an EDM experiment, arises as follows. The average vertical position of a beam in a storage ring with dipole and quadrupole magnetic fields will be where the radial magnetic field is zero:

$$F_v = ec\beta B_r = 0 \tag{4}$$

A non-zero radial magnetic field will precess the spin in the vertical plane generating a false edm signal:

$$d\vec{S}/dt = \vec{\mu} \times \vec{B} \tag{5}$$

With electric and magnetic fields, the Lorentz force is:

$$\vec{F} = e(\vec{E} + c\vec{\beta} \times \vec{B}) \tag{6}$$

In the EDM experiment, the nominally horizontal electric field seen by the muons must be accurately in a plane; otherwise, the out of plane component of the field (E_v) will induce a net average radial component of the magnetic field:

$$B_r = \frac{E_v}{\beta c} \tag{7}$$

Specifically, the average height of the beam will change until the average force is zero, and the resulting average radial magnetic field will precess the spin in the vertical plane generating a false EDM signal.

We plan to measure this effect with a polarized deuteron beam. Due to the much lower value of β of the deuteron, the deuteron spin is much more sensitive to an out of plane electric field component and much less sensitive to a deuteron EDM. Present theoretical limits on the deuteron EDM are too small to affect this measurement [42].

The signal to systematic error ratio (Figure 2, top right) for a fixed misalignment angle of the electric field vs the muon momentum is shown. Above a certain momentum the ratio does not vary significantly. In the lower left is shown the required B-field versus the muon momentum and in the lower right the required E-field strength versus the muon momentum.

In the LOI [1] we proposed to use the current E821 muon storage ring. With a view to reducing the systematic error due to E_v, we are also actively investigating schemes which would use dedicated storage rings instead of the muon g-2 ring. One such scheme would have two circular rings, B-field only, separated by straight sections with mainly E-field plus a small B-field to cancel the bending due to the E-field.

There are advantages to having the E-field applied in a straight section rather than in the region of the B-field. By having the muons pass through the straight sections in opposite directions, E_v will automatically average to zero. Also, there are many practical benefits of separating spatially the electric and magnetic fields.

We are requesting R&D funds for development of both the E-field for the storage ring as well as for a deuteron polarimeter to measure the E-field systematic error effect.

4 Possible Ring Configurations

The configurations involving the current g-2 ring are described in the attached LOI. Here we discuss dedicated storage rings which are being considered as an alternative.

4.1 DC E-field Configuration

One possible configuration is shown in Figure (3a,b). The B-field direction is out of the page and the paths of positive muons are shown. The middle sections have an electric field with a small magnetic field to keep the trajectory straight. The arc sections have only B-fields.

The B-field causes the g-2 and EDM precessions while the applied E-field cancels the g-2 precession. By interchanging the muon direction in the straight paths and the E-field direction at the same time, as is shown in Figure (3b), the average out of plane E-field component cancels. This cancellation is exact when the muon distribution and the E-field uniformity is kept the same in the two sections. The quality of the electric field is determined by the flatness of the side plates. Part of this R&D effort is to determine the level of flatness obtainable and to build ultra-sensitive inclinometers to monitor this flatness as a function of time [43]. The magnetic field uniformity and directional stability is not essential to the EDM experiment and strong focusing will be used to increase the number of stored muons.

4.2 AC E-field Configuration

Another possible configuration is shown in Figure (4). In this case instead of the two parallel straight sections with opposite E-fields, we use a single straight section with an alternating RF E-field synchronized to the muon orbit frequency. The bunch length needs to be short. The out of plane electric field automatically cancels.

4.3 Request for R&D Funds to Develop the Optimum E-field

We request R&D funds to build and test prototype dipole electric field modules and for support for an accelerator physicist consultant. As mentioned above exciting progress has been made during the R&D for future accelerators in understanding the requirements for obtaining large electric fields. However, our electrode geometry is quite different. We cannot choose the optimum ring configuration until we understand the electric field constraints for our electrode geometry. Our request is:

1. One post doc to work on the development of the electric field modules. This includes the development of the highest possible electric field strength, as well as the requirements for alignment and E-field uniformity. It also includes the development of the monitoring of the electrode structures with laser interferometers and ultra-sensitive inclinometers [43].

2. A mechanical technician full time to construct the electric field modules and the inclinometers.

3. Support for an accelerator physicist consultant.

4. Travel support for consulting with experts as required.

The cost for this R&D including BNL overhead is:

Cost Estimate for Electric Field and Ring Lattice Development	
Equipment and Supplies:	
Materials, power supplies, shop time	$ 125,000
Personnel:	
Post-doctoral research assistant (1 year)	40,000
Accelerator physicist (half year)	54,000
Technician	72,000
Travel:	5,000
Total:	$ 296,000

4.4 R&D Request for the Deuteron Polarimeter

As explained above, any net out of plane electric field will generate a false EDM signal. In the final EDM ring we must certify that this error is less than $10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$. We plan to measure the effect using polarized deuterons which have a negligible EDM [42] but can generate a larger false EDM signal. Polarized deuterons can be available from the AGS but we need to develop a deuteron polarimeter with an angular sensitivity of 40μrad.

The present polarimeter design as shown in Figure (5) calls for a CH_2 target which intercepts the deuteron beam. Elastic scattering from both the carbon and hydrogen components is sensitive with nearly the same analyzing power to the vector polarization of the deuteron beam. One straightforward detector design would use a shingle-stack of 8 plastic scintillators spanning the laboratory angles between $19°$ and $60°$ on both the left and right sides of the beam for a total of 16 scintillators.

There are several goals in building a prototype:

1. The CH_2 target must present a small area to the circulating deuteron beam ($\leq$ 0.03 mm^2) in order to maintain beam lifetime in the storage ring while being thick to the beam. If the thickness can be as large as 1.5 mm without compromising the ability to distinguish elastic events, then the polarimeter efficiency can become as large as 2×10^{-4}, a value that is required in order to conduct the ring field test in a reasonable amount of time.

2. To map the sensitivity of the polarimeter to the systematic errors of beam misalignment and misdirection. These will affect carbon and hydrogen scattering differently and a comparison of these two components can provide the tools for developing corrections.

3. To explore the response of the polarimeter to very high rates. These rates will change over the time of the measurement during which we need to be able to extract the required information on the precession of the deuteron spin axis.

4. To demonstrate that an operable polarimeter can be constructed that will yield signals of sufficient quality.

Support during FY2002 would allow us to make use of the Cooler ring, a synchrotron located at the Indiana University Cyclotron Facility (IUCF), that offers polarized deuteron beams at the required energy. Particularly important is the ability to use very small solenoidal fields to make modifications to the stable spin direction of the stored beam orbit that would be comparable to the size of the effect we expect to observe at Brookhaven. After that time, NSF support for ring operations ceases and access to the Cooler for testing is uncertain.

An estimate of the costs to develop, build, and begin testing a polarimeter are detailed in the table below. It is assumed that the polarimeter would be a stand-alone system that could be moved from IUCF to Brookhaven and made to operate with very few installation changes. The modular electronics would handle 16 channels with programmable discriminators and a programmable logic module to generate triggers for the various combinations of scintillator hits. Additional logic is needed to handle busy gating and to prescale events from each stream. Time and pulse height information is to be recorded for computer analysis. IUCF would provide the XSYS data acquisition system (already developed and in use).

It is anticipated that the development and design of this polarimeter, and its subsequent construction and testing, would be the full time occupation of one person on the scientific staff at the post-doctoral level. The rate given includes starting salary and fringe benefits along with a 49% university overhead charge. If a graduate student were to take this on as a project, salary, fee remission, and overhead would be an additional $ 33,000 per year. In addition, we would expect to need roughly two person-months of shop and technical support to make the scintillators, support structure, and targets needed for polarimeter tests.

Cost Estimate for Polarimeter Development

Equipment and Supplies:	
scintillator stock, shop materials, parts	$ 2,500
photomultiplier tubes	7,000
modular electronics	48,000
electronics crates	6,000
delay cable, connectors	2,000
multi-channel high-voltage power supply	10,000
VME computer front end	10,000
PC computer with Linux for data acquisition	3,000
Personnel:	
shop and technical support (2 months)	15,000
post-doctoral research assistant (1 year)	68,000
Total:	$ 171,500

It is expected that if support were available soon, a prototype could be designed and made ready for installation within a year, and that the first round of tests could be completed. The studies and refinements needed to meet the requirements of the EDM experiment would continue into the second and third years.

5 Summary

Recent developments such as the experimental result for the muon g-2, the theoretical understanding of the muon EDM, and the progress in reliably making much higher E-fields, enhance the importance, the sensitivity and the practicality of an EDM experiment for the muon.

In order for us to be able to submit within the next year a proposal for a muon EDM measurement capable of reaching 10^{-24} $e \cdot \mathrm{cm}$ sensitivity we need a total of $467.5K. $296K are to be used on the R&D related to the electric field plus support for an accelerator physicist to work on the storage ring design. The other $171.5K are to be used on the development of the deuteron polarimeter at the Indiana University Cyclotron Facility (IUCF).

6 Appendix

Update of the LOI Deuteron Polarimeter Section

From recent work with the deuterium negative ion source at IUCF [44], it would appear reasonable to expect that deuteron polarizations that are about 85% of their maximum value can be achieved. With multiple stages of inhomogeneous magnetic field and rf transition to separate the deuteron spin states, it is possible to select very large maximum polarization values. In spite of their tensor polarization, statistical considerations would suggest the use of the pure $m = 1$ and $m = -1$ magnetic projections of the deuteron spin along the momentum direction.

A reasonable sensitivity to the vector polarization is available with either a hydrogen or a carbon target at 42 MeV. We will consider each in turn. For consistency of notation, we will use the Cartesian system.

At 42 MeV, the vector analyzing power for deuteron scattering from hydrogen is largest ($A_y < -0.17$) in the range $\theta_{c.m.} = 84°$ to $121°$ [45, 49]. The scattered deuterons emerge between 18° and 27° in the lab, and the recoil protons appear between 41° and 60°. Both particles can be detected in plastic scintillators, even though their ranges are less than 6 mm. Polarimeters based on proton-deuteron elastic scattering at higher energies can select elastic scattering events on the basis of scintillator pulse height and relative time of flight [48]. Segmentation of the scintillator readout will be needed to allow for changes in the time of flight with changing scattering angle. Integration over all azimuthal angles and the range in scattering angle described above yields a cross section of 15.7 mb and a weighted average analyzing power of $A_y = -0.25$. If the target is a composite material such as CH_2, the main background will be (p,2p) events originating in the carbon.

At the same bombarding energy, forward angle deuteron scattering from carbon also exhibits a negative analyzing power lobe [46]. In the angle range from $\theta_{\rm lab} = 30°$ to $43°$ the integrated cross section is 37.9 mb and the weighted average analyzing power is $A_y = -0.28$.

Both of these processes can be observed simultaneously in a polarimeter instrumented between $\theta_{\rm lab} = 18°$ to $60°$. If scintillator about 6 mm thick is used, deuterons elastically scattered from carbon will punch through. A double scintillator layer will provide a coincidence tag and the relative pulse heights can distinguish the deuteron from proton background. Thus deuteron scattering from carbon and hydrogen will have unique signatures. If the space if confined (e.g. the g$-$2 ring) then there is a premium on minimizing the number of scintillator segments that require independent light guides and readouts. A higher degree of segmentation can be achieved by overlapping neighboring scintillators in a shingle arrangement, and by staggering in angle the boundaries for observing proton-deuteron coincidences between the proton and deuteron scintillators.

The polarimeter target should have a small cross sectional area presented to the beam in order to maintain long beam lifetimes. With collimating slits set for 6×48 mm^2, a target with a round area 0.2 mm in diameter produces a lifetime of about 4000 turns [47]. The same slits yield a momentum acceptance of better than $\Delta p/p = 2 \times 10^{-4}$, and the de-coherence of the polarization takes places in roughly the same number of turns (for the g-2 ring case). At the same time the target material can be deeper along the beam direction to improve the efficiency of the polarimeter. A thickness of 1.5 mm creates an energy loss of about 4 MeV for beam deuterons; much more degrades the range separation scheme described above. Such a target can be in the form of a thin strip that is stretched across the beam, or formed into a rod suspended in the middle of the acceptance.

Space confinement suggests that perhaps 40% of the azimuth can be instrumented, providing a cross section for both processes of about 28 mb. If the 1.5-mm target is composed of polyethylene (CH_2), the efficiency of the polarimeter will be 1.7×10^{-4}. Thus an estimate of 10^7 deuterons per fill will, in one beam lifetime, lead to about 10^3 detected events. Rates in individual scintillators will be approximately 10^5 /s, suggesting that discrimination of the individual events should be handled within the electronics and only sampled for detailed computer analysis.

To achieve an error on the measurement of the muon electric dipole moment of $10^{-24}\,\mathrm{e}\cdot$ cm, the out of plane electric field component must be known to ± 10 nrad. The deuteron, mainly because of its lower velocity, is some 6 times more sensitive to the angle of mis-alignment. This, along with the deuteron's longer lifetime in the g$-$2 ring, leads to a level of precision of $\delta\theta_{\mathrm{d}} = \pm 50$ μrad that is needed in order to certify the field alignment.

The number of events needed in order to achieve this level of precision is obtained from the error on the left-right asymmetry that will be required. This is $\delta\epsilon = 3\ \delta\theta_{\mathrm{d}}\ p\ A_y/2 = 1.7 \times 10^{-5}$; leading to an event count of $C = 1/\delta\epsilon^2 = 3.5 \times 10^9$. Small asymmetries of this order are hard to measure absolutely because of the necessity to cancel systematic errors to the same level. For this application, however, it is only necessary to measure a change of this size that occurs during the time of the measurement. A lifetime of 4000 turns requires about 3 ms. This time should be segmented into at least three bins; thus 10^{10} events are needed. If there are 5 fills/s for the g$-$2 ring, then it takes roughly 3 weeks to accumulate the required statistics.

There are a number of simple strategies that reduce systematic errors in leading order. One, mentioned above, is that it is not necessary to cancel all such errors, as only a change needs to be observed. However, the error is reduced by placing detectors on the left and right sides of the beam, and alternating between positive and negative polarization states in some rapid sequence. Then the asymmetry is given by

$$\epsilon = \frac{3}{2}\, pA_y = \frac{r-1}{r+1} \qquad \text{where} \qquad r^2 = \frac{L_+R_-}{L_-R_+}$$

and the count rates for left (L) and right (R) are separated according to positive and negative polarization states. In this cross ratio formulation, efficiency differences between left and right systems, and run time differences between the two polarization states, are cancelled in the calculation of r. In addition, it is important to insure that the target mounting does not introduce the opportunity for breaking these simple symmetries.

Figure (5) shows one possible placement of the major polarimeter components. In this plan, the target is shown as a thin strip of CH2 suspended horizontally between two mounting blocks (shown with hash lines) so that the thin edge is presented to the beam. The component of the deuteron polarization to be measured is vertical. On the left and right sides of the beam are two arrays of eight scintillators. They are mounted to form a segmented array two scintillators deep except for the ends. Elastic scattering from hydrogen is observed by the three scintillators on either end of the array of eight. Coincidences would be formed between a forward scintillator on one side with a rear scintillator on the other side. The staggering of the boundary angles (dot-dash lines) is such that they fall between each other kinematically, thus doubling the segmentation. The four scintillators in the middle of the array also observe and trigger on deuteron scattering from carbon using a coincidence between two scintillators that are along a straight line path from the target. The deuteron and proton from hydrogen scattering will penetrate only one scintillator deep on either side. The height of the scintillators spans the azimuthal angles where polarization effects from the vertical vector component are the largest. Solid light guides (not shown) would be needed to transmit signals to phototubes mounted outside the ring.

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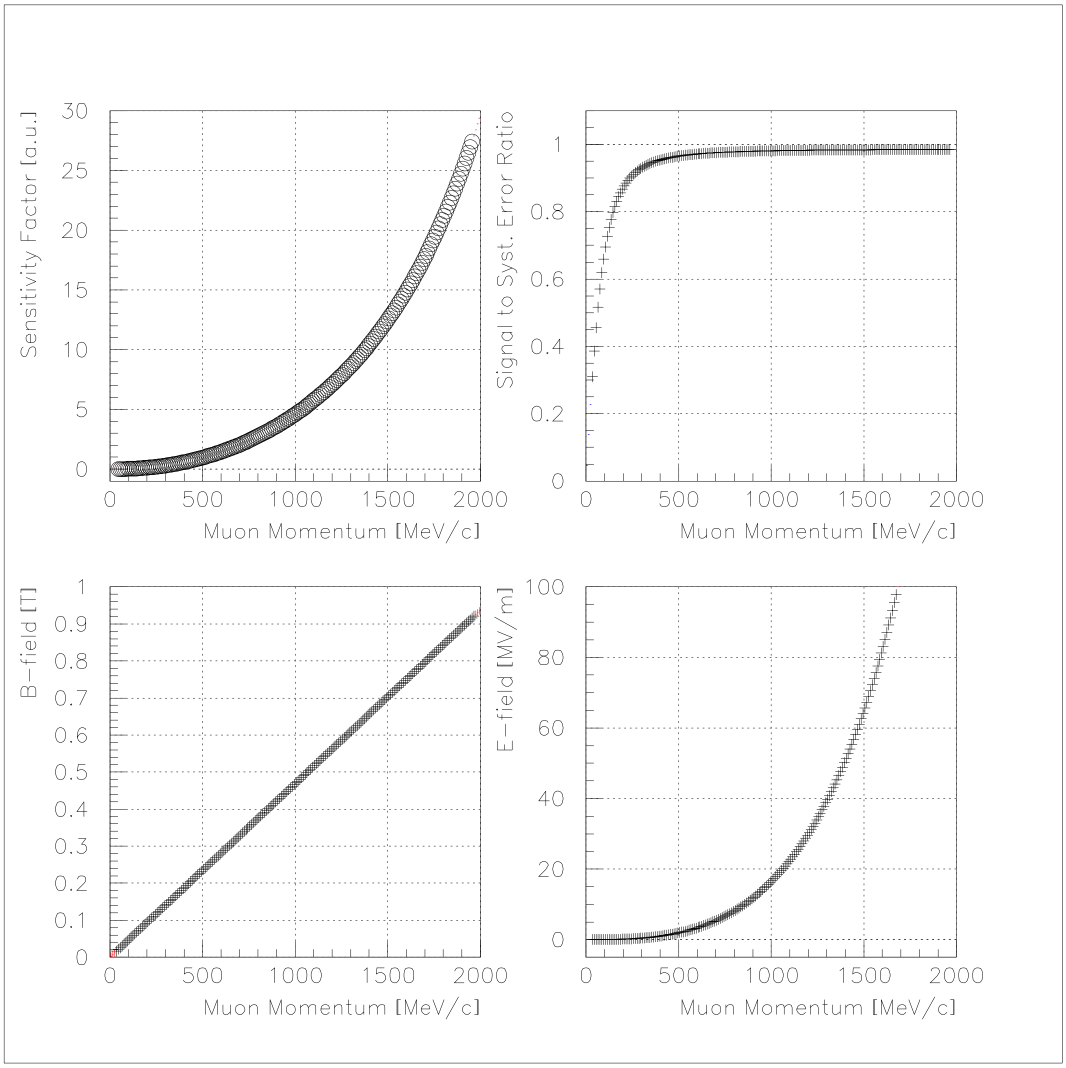

Figure 2: Top left: The sensitivity factor versus the muon momentum when there is an electric field cancelling the g-2 precession (the sensitivity is taken as equal to 1 at 500 MeV/c). It is assumed that the ring radius is 7.11 m, i.e. same as in the muon g-2 ring. The sensitivity to the muon EDM increases by a factor of 15 going from 500 to 1600 MeV/c. This does not take into account the increase of the statistical sensitivity due to the higher acceptance of the ring.

Top right: The signal to systematic error ratio for a fixed misalignment angle of the electric field vs the muon momentum is shown. Above a certain momentum value the ratio is constant.

Lower left: The required B-field versus the muon momentum and

Lower right: The required E-field strength versus the muon momentum.

Figure 3: The top view (and cross section of the E-field shown here with a net misalignment) of a possible ring configuration in a dedicated muon EDM experiment with a DC E-field.

a) The E-field region is only present in the straight section and the field direction is such that it cancels the g-2 precession.

b) The E-field direction is flipped and the muon beam direction also changes to comply with the above requirement to cancel the g-2 precession.

In this case the out of plane E-field component (the main systematic error) is automatically cancelled.

Figure 4: The top view of a possible ring configuration in a dedicated EDM experiment with an AC (RF) E-field orthogonal to the muon momentum. The E-field region is only present in the straight section and is in phase with the muon bunch so that its direction alternates depending on the muon momentum direction. This way the net out of plane E-field component (the main systematic error) is automatically cancelled.

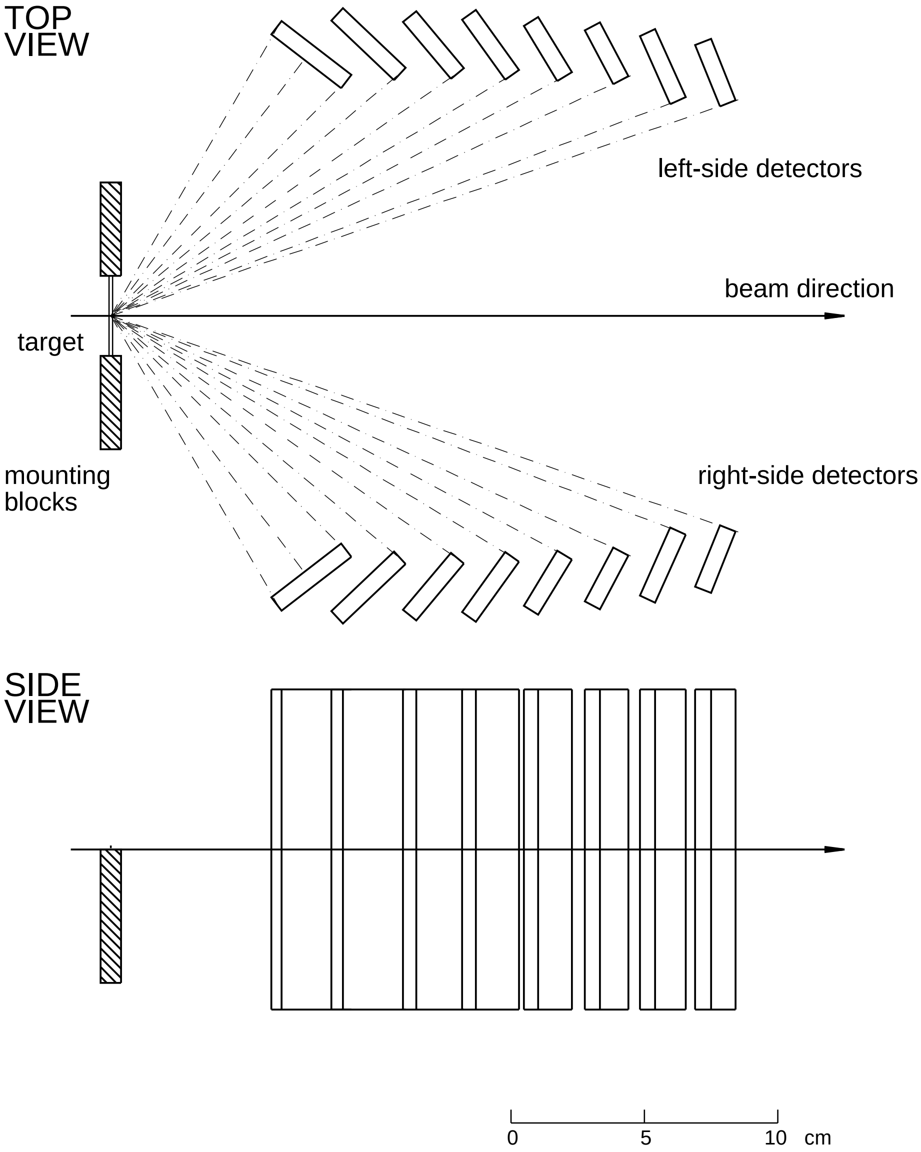

Figure 5: The top and side view of the deuteron polarimeter.