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Experiment to measure the EDM of Muon

Yannis K. Semertzidis, Brookhaven National Laboratory

Francis J.M. Farley, Yale University

Donald Lazarus, William M. Morse, Brookhaven National Laboratory

B.L.Roberts, Boston University

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The $(g-2)$ angular precession frequency of the muon spin relative to the momentum vector in combined vertical magnetic field B_0 and horizontal electric field E_0 is

$$\omega_a = [aB_0 + (\frac{1}{\gamma^2-1} - a)\frac{\beta E_0}{c}](e/mc) \tag{1}$$

where $a = (g-2)/2$ is the muon anomalous magnetic moment. To measure the electric dipole moment (edm) it is proposed to use a large radial electric field E_0 so that ω_a is reduced to zero. The muons then keep their forward polarization with no horizontal precession.

In the rest frame there is a horizontal electric field $E^* = \gamma\beta B$ induced by the Lorentz transformation. If there is an edm of magnitude $\eta \times (eh/4\pi mc) = \eta \times 0.93 \times 10^{-13}\ \mathrm{e \cdot cm}$, then the spin will precess in the vertical plane at angular velocity

$$\omega_e = \eta\beta B_0(e/mc) \tag{2}$$

(The factor γ is eliminated by time dilation when we transform back to the laboratory frame).

If the $(g-2)$ precession is active then the combined effect is to tilt the plane of precession out of the horizontal by the small angle $\delta = \beta\eta/a$. In effect the edm starts to swing the spin out of the horizontal plane, but this effect is reversed and cancelled when the spin direction reverses because of the $(g-2)$ precession, so the overall effect is small. This has led to the current limit of about $3 \times 10^{-19}\,\mathrm{e \cdot cm}$.

But if the $(g-2)$ rotation is cancelled by applying the radial electric field, the edm precession operates on its own and the vertical angle can accumulate over many microseconds. To get $\omega_a = 0$ in 1 , we need

$$E_0/c = \frac{aB_0(\gamma^2-1)}{\beta(1-a(\gamma^2-1))} \tag{3}$$

(The term in a in the denominator will be only 0.028 in the chosen conditions and will be neglected for simplicity).

But for a fixed storage radius ρ_0

$$B_0 = \frac{\beta\gamma mc}{e\rho_0} \tag{4}$$

Therefore

$$E_0/c = \frac{amc\gamma(\gamma^2-1)}{e\rho_0} \tag{5}$$

We see that the electric field required to cancel the $(g-2)$ precession varies as γ^3. To get a good measurement we therefore need to use the highest possible electric field and thus operate at the highest available γ.

A good practical compromise occurs at kinetic energy 420MeV with $\gamma = 5$, $\beta = 0.98$, muon lifetime 11μs. For radius 711cm the magnetic field is then $B_0 = 2.4$kG and the average radial electric field required is

$$E_0 = 21\,\mathrm{kV/cm} \tag{6}$$

We will observe the vertical precession for ten lifetimes with decay electron detectors above and below the orbit. If 10^{12} decays are recorded and the asymmetry for total vertical polarization is 0.2, then we would be sensitive to a vertical angle $\theta_e = 5\mu$R. Using 2 we then find

$$\eta = \frac{\theta_e}{\beta B_0(e/mc)t} = 8 \times 10^{-10} \tag{7}$$

with $e/mc = 8.53 \times 10^8 \,\mathrm{rad\,s^{-1}\,T^{-1}}$. So the limit of sensitivity for the edm would be $8 \times 10^{-23}\,\mathrm{e \cdot cm}$.

At these fields the $(g-2)$ period would be 22μs. We want to cancel the horizontal precession over the whole aperture for 100μs, so the cancellation should be good everywhere to about 1 part in 400. This is not trivial because

(a) At this muon momentum ω_a varies with radius,

(b) the horizontal electric field, if made by cylindrical electrodes, will naturally decrease as $1/\rho$, and

(c) γ varies with radius.

However we can compensate at all radii if we combine a radial magnetic gradient (field coefficient n_m) with electric quadrupoles giving an effective field coefficient n_e. From eqn(3), with a little algebra, the criterion for cancellation over the whole aperture is

$$n_e = \frac{a\gamma_0^2(n_m - 2)(1 - n_m - n_e)^2}{\beta^2} \tag{8}$$

where $a\gamma_0^2/\beta^2 = 1/38$.

One of many possible solutions is $n_m = 0.25$, $n_e = -0.06$ so the effective combined gradient is $n_{eff} = 0.18$ To understand this combination note that γ increases with radius, but the radial electric field from the cylindrical electrodes decreases with radius. Further B decreases slowly with radius. In combination we need a negative value of n_e to get the correct radial dependence of E to match eqn(3) everywhere. Negative n_e is horizontally focusing; it reduces E at small radii and increases it at large radii.

Beam intensity and statistics

In this experiment we are looking for a vertical asymmetry which slowly increases with time. Any fixed asymmetry due to differences between the up and down electron detectors will not interfere.

An estimate of the number of stored muons is obtained by comparison with the predictions for the $(g-2)$ experiment.

E821 will store 2.4×10^{11} muons in 400 hours of dedicated muon injection running at 6μA AGS average current. The AGS current is expected to be 15μA by the year 2000 with tuning and barrier buckets. If the accumulator is built and the AGS power supply is upgraded to 2.5Hz, the current is anticipated to be 40μA. For E821 with a 3.1 GeV/c pion beam, 38% of the pions decay to muons from the pion selection slit at 8.7m to the pion rejection slit at 97.5m. For the 0.5 GeV/c beam 70% decay in this region. The E821 pion/muon beamline collects pions within 32mrad horizontal × 60mrad vertical with a momentum acceptance of 2% base-width, ie. 60MeV/c. The polarization is high: 97% for pion injection; somewhat less for muon injection. The flux of 0.5 GeV/c pions within this acceptance is much less than 3.1 GeV/c pions. $d^2N/dpd\Omega$ is less by a factor of about three from Hagedon and Randft, and dp is less by the ratio of 0.5 to 3.1.

Change	Intensity Factor
15μA (barrier buckets)	2.5
40μA (accumulator)	6.7
0.5 GeV/c Pions	0.06
Muon Decays	1.8

The number of stored muons is then down to 0.70 compared with (g-2) even with the AGS accumulator. What is needed is a much larger acceptance beamline with matching acceptance in the storage ring maintaining the polarization. Note that in the $(g-2)$ experiment the acceptance is a good match to the rate capabilities of the detector (primarily systematic shifts in timing at high rates) and the weak electrostatic focusing at the magic gamma necessary to know the magnetic field at the required high accuracy. But for the new edm measurement different criteria apply.

We conclude that with a weak focusing ring and without the accumulator we will only be able to process about 6×10^{10} decay electrons in a 400 hour run, so the limit on the muon edm would be $3 \times 10^{-22}\,\mathrm{e \cdot cm}$. We are studying the possibility of increasing the acceptance of the ring by using strong focusing and adapting the muon decay channel to correspond. This might be able to increase the stored intensity by a factor of 100-300, so that about 2×10^{13} decays could be recorded in 400 hours. Then the edm might be measured to order $2 \times 10^{-23}\,\mathrm{e \cdot cm}$. A further improvement by raising the electric field by a factor of 2, and using a lithium lens at the production target to collect more pions are under investigation. In combination to running for longer than 400 hours might bring us well into the $10^{-24}\,\mathrm{e \cdot cm}$ region.

Note that by increasing the energy of the pions entering the decay channel we can select muons from backward decay with polarization reversed. The up/down asymmetry generated by the edm should then be opposite. Although the beam intensity would be smaller, this is a good way to cancel some of the residual systematic errors.