Muon EDM Experiment Using Stage II of the Neutrino Factory

R.C. Fernow, J.C. Gallardo, W.M. Morse, and Y.K. Semertzidis
Brookhaven National Laboratory

During the second stage of a future neutrino factory unprecedented numbers of bunched muons will become available. The cooled medium-energy muon beam could be used for a high sensitivity search for an electric dipole moment (EDM) of the muon with a sensitivity better than 10^{-24}e · cm. This will make the sensitivity of the EDM experiment to non-standard physics competitive and in many models more sensitive than the present limits on edms of the electron and nucleons. The experimental design exploits the strong motional electric field sensed by relativistic particles in a magnetic storage ring [1, 2].

1. Introduction

The discovery of an intrinisic electric dipole moment would indicate a new source of CP violation and point to physics beyond the standard model. A fundamental particle is described by only a few parameters, such as its mass, its intrinsic angular momentum, its electric charge (electric monopole moment), its magnetic dipole moment. A permanent EDM violates both parity (P) and time reversal (T) invariance. If CPT is assumed to be valid, a permanent EDM would hence be a signature of CP violation [3]. The standard model of particle physics predicts a CP violating EDM in fundamental particles more than five orders of magnitude below the sensitivity of present experiments [4]. Therefore searches for a permanent EDM render excellent opportunities to test models beyond standard model.

The Muon g-2 Experiment, E821, now being conducted at BNL, has been designed to probe physics beyond the standard model [5]. This includes super-symmetry (SUSY) with large $\tan\beta$ where the muon EDM also has sensitivity. The experiments complement each other, as the magnetic anomaly and the EDM are related to each other as real and imaginary parts of the same physical quantity [6, 7]. The new result on the muon magnetic anomaly [8] corresponds to a dipole moment of 3.5×10^{-22}e · cm [9], for a CP-violating phase of order 1. There are recent L–R SUSY models [10] using the see-saw mechanism to provide for the observed finite neutrino mass, where the EDM contribution could be as large as 5×10^{-23}e · cm and the electron EDM is well below the present limit [10].

The muon EDM will cause the muon spin to precess about the direction of the E-field. In a storage ring such a field exists because the external B-field is partially converted to an electric field in the muon rest frame due to the Lorentz transformation. For example, the external dipole magnetic field used in the muon g-2 ring of ≈ 1.5 T is partially transformed to an effective electric field of ≈ 450 MV/m. The directions and energies of the decay electrons are correlated to the muon spin direction. In particular, when the plane of spin precession is tipped out of the plane of the storage magnet the decay electrons will have average upward and downward momentum components as the muon spin moves up or down. Using this principle, the last muon g-2 experiment at CERN reported [11] a limit of $3.7 \pm 3.4 \times 10^{-19}$e · cm. The error is the combined result of the statistical and systematic errors: $\pm 2.7 \times 10^{-19}$e · cm and $\pm 2 \times 10^{-19}$e · cm, respectively.

2. Experimental Overview

The muon spin precession angular frequency relative to the momentum vector 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

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

assuming the muon velocity is orthogonal to the external magnetic and electric fields ($\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$). η plays a role for the EDM corresponding to the g factor for the magnetic dipole moment.

From the above equation, it is clear why the present $g-2$ experiment uses the “magic” $\gamma = 29.3$, 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 as well as a radial electric field which cancels the g-2 precession leaving the EDM precession to operate on its own and accumulate over many microseconds. It should be noted that the main component which causes the spin to precess vertically in the muon rest frame is the lab dipole magnetic field which is partially transformed into a radial electric field in the muon rest frame. The electric field in the lab required to cancel the g-2 precession is

$$E = \frac{aBc(\gamma^2 - 1)}{\beta(1 - a\gamma^2 + a)} \tag{3}$$

3. Neutrino Factory

The goal of a sensitivity of 10^{-24}e · cm requires the number of muon decays times polarization squared of $NP^2 = 10^{16}$. This is not possible in a reasonable amount of running time without neutrino factory technology. During the construction of a NF a number of particle beam resources would become available, which could be used for other physics purposes. One possible scheme for staging the construction of the NF project is given in Table I.

Table I Neutrino Factory Project Phases

Phase 1	High power proton driver and target	0 – 24GeV/c
Phase 2	Front end through cooling	μ: 200 MeV/c
Phase 3	Complete linac	μ: 2.5 GeV/c
Phase 4	Complete RLA and storage ring	μ: 20 GeV/c

3.1. Phase 1 Proton driver

The first phase of the NF would involve the construction of a high power proton driver and a target station. A proton driver with a beam power of 1–4 MW and a target system that can handle this power level opens the door to the study of many physics topics. Table II lists some properties of the 1 MW configuration of the proton driver.

3.2. Phase 2 muon beam parameters

Upon the completion of phase 2 of the NF project, there will be available a high-intensity cooled muon beam with the properties listed in Table 3. This muon beam has a total intensity of $4 \times 10^{13}\mu/s$. The time structure is very complex. There is an overall 400 ms cycle time. Inside this there are 6 bursts of muons separated from each other by 20 ms. Each burst is further subdivided into 67 individual muon bunches separated from each other by 5 ns.

Although the muon intensity is very high, there are a number of attributes of this beam that makes it unsuitable for many muon experiments. The beam momentum of 200 MeV/c is relatively high for experiments that require muons stopped in a thin target. The rms momentum spread of 10% is also high, while the polarization of 16% is low. In addition, the beam has a bunched

Table II Proton driver parameters

$\langle P\rangle$	24	GeV/c
σ_p	0.12	GeV/c
σ_x	1.5	mm
σ_t	3	ns
N_p/bunch	1.7×10^{13}	
N_{bunch}	6	
Time between bunches	20	ms
f_{rep}	2.5	Hz

Table III Muon beam parameters

$\langle P\rangle$	203	MeV/c
σ_p	21	MeV/c
σ_x	15	mm
σ_x'	94	mr
bunch spacing	5	ns
σ_t	0.51	ns
N_μ/bunch	4.2×10^{10}	
N_{bunch}	6×67	
Time between bunches	20	ms
f_{rep}	2.5	Hz
Polarization	0.16	

time structure, which is unsuitable for coincidence experiments. The experiment that would be improved using this beam is the search for the electric dipole moment (EDM) of the muon.

If there are strong reasons for using a momentum higher than 200 MeV/c, the beginning sections of the linac could be included in this phase of the NF project in order to accelerate the muons to the required momentum. The NF time structure seems fine for this experiment since the muons would be injected into the ring over the 340 ns bunch train length and then 20 ms would be available for the measurement before the next train of muons arrived. The NF produces a muon beam with a potential NP^2 factor 10^{12} per second. This could, in principle, produce the required sensitivity level for the experiment in 10^4 seconds. In practice mismatches between the muon beam emittance and the likely ring acceptance will degrade the effective NP^2 factor. The momentum spread of the beam (10%) is large compared to typical ring designs (1%). If the length of the bunch train (100 m) is larger than the circumference of the ring, there may be additional injection losses. Unless the ring has a large aperture, there will be additional losses from the transverse size and divergence of the beam. Until a ring is designed it is not possible to make a firm estimate of these losses, but a factor of a few times 10^{-3} seems like a reasonable first guess. This would imply that the required sensitivity could be reached in less than a year of running.

References

[1] Y.K. Semertzidis *et al.*, Letter of Intent to the AGS of BNL (1997)

[2] Y.K. Semertzidis *et al.*, p. 81, KEK international workshop on High Intensity Muon Sources, Tsukuba, Japan, Dec 1–4, 1999, Yoshitaka Kuno, and Takeichiro Yokoi (eds.), World Scientific (1999) and Y. Semertzidis *et al.*, “Sensitive Search for a Permanent Muon Electric Dipole Moment”, arXiv:hep-ph/0012087, 2000.

[3] S.M. Barr and W. Marciano, in CP Violation, ed. C. Jarlskog, World Scientific, Singapore (1989)

[4] I.B. Khriplovich and M. Pospelov, Nucl. Phys. **B 420**, 505 (1994); F. Hoogevenn, Nucl. Phys. **B341**, 322 (1990); I.B. Khriplovich, Phys. Lett. **B 173**, 193 (1986)

[5] T. Kinoshita and W.J. Marciano, in Quantum Electrodynamics, ed.T. Kinoshita, World Scientific, Singapore, p. 419 (1990); J.L. Lopez, D.V. Nanopoulos and X. Wang, Phys. Rev. D**49**, 366 (1994); U. Chattopadhyay and P. Nath, Phys. Rev. D**53**, 1648 (1996); T. Moroi, Phys. Rev. D**53**, 6565 (1996); A. Czarnecki and W.J. Marciano, Nucl. Phys. (Proc. Suppl.) **B76**, 245 (1999).

[6] W.J. Marciano, HIMUS Workshop, Tsukuba, Dec 1–4 (1999).

[7] W.J. Marciano, Lepton Moments Workshop, Heidelberg (1999).

[8] H.N. Brown *et al.*, Phys. Rev. Lett. **86**, 2227 (2001).

[9] W.J. Marciano, private communication.

[10] K.S. Babu, B. Dutta and R.N. Mohapatra, Phys. Rev. Lett. **85**, 5064 (2000); K.S. Babu presentation at the EDM2001 Workshop, May 14-15, Brookhaven National Laboratory (2001).

[11] J. Bailey *et al.*, Nucl. Phys. **B150**, 1 (1979)