Sensitive Search for a Muon Electric Dipole Moment

Using the Present Muon g-2 Ring

$10^{-18} \text{e.cm} \rightarrow 10^{24} \text{e.cm}$

Probing the 2\textsuperscript{nd} generation for CP-Violation

\[ \frac{d\vec{s}}{dt} = \vec{d}_{edm} \times \vec{E} \]
Outline:

- Motivation of Muon EDM
- Principle of EDM Experiment
- Experimental Design
- Systematics
- Summary
Electric Dipole Moment

\[ \vec{d}_\mu \propto \text{Spin Vector} \]

Violates both P & T Symmetries

[Diagram showing CPT and CP]

1ppm in g-2: \[ \frac{\Delta g}{g} \frac{e}{2m} \sim 10^{-22} \text{ e} \cdot \text{cm} \]

2nd generation and CP "Crisis"
Muon $g-2$ Results

Measurements (1-4) and Projections (6, 7)
Electric Dipole Moments in Supersymmetric Theories

Apostolos Pilafitis (CERN)

- CP-violating phases in the MSSM

- One-loop contribution to EDMs and CP crisis (Schemes of resolving the CP crisis)

- Two-loop contribution to EDMs (New two-loop contribution to EDMs)

- Three-loop contribution to EDMs

- Conclusions
Conclusions

- Supersymmetric theories predict large EDMs at the observable and higher level.

- Schemes of resolving the CP crisis:
  1. CP phases $\approx O(10^{-2})$; $M_{\tilde{f}}, m_{\chi} \sim 200$ GeV
  2. CP phases $\approx O(1)$; $M_{\tilde{f}} \geq 1$ TeV, for the first two generations only. There is still a large two-loop EDM contribution due to super-BZ-type graphs involving the third generation.
  3. Non-universal trilinear $A_f$ couplings or cancellation mechanism.

- New experiments of lepton- and quark- EDMs beyond the first generation are very important, e.g. $\mu$-EDM.
to the statistical error and the second to the systematic.

Stronger than linear ($x < 0$). The number in the first parentheses for the electron case refers
and neutrons ($n$). For various speculative models the scaling with the lepton mass is

For protons ($p$), muons ($\mu$), taus ($\tau$), electrons ($e$), and muons ($\mu$), neutrons ($n$), and protons ($p$).

| $x_{\mu}$ | $x_{\pi}$ | Present Limit on $|p|$ | New Physics Limits | Standard Model Prediction |
|----------|----------|----------------|-------------------|--------------------------|
| $0.5\times 10^{-3}$ | $0.5\times 10^{-3}$ | $6.3 \times 10^{-2}$ | $90\%$ C.L. | $1.05 \times 10^{-18}$ | $1.8 \times 10^{-27}$ | $e$ |
| $0.6 \times 10^{-3}$ | $0.4 \times 10^{-3}$ | $3.1 \times 10^{-16}$ | $95\%$ C.L. | $1.0 \times 10^{-18}$ | $1.2 \times 10^{-27}$ | $n$ |
| $1.1 \times 10^{-3}$ | $1.0 \times 10^{-3}$ | $6.3 \times 10^{-23}$ | $10^{-22}$ | $6.3 \times 10^{-23}$ | $10^{-22}$ | $d$ |

Table 1: Limits on Electric Dipole Moments for Electrons ($e$), Muons ($\mu$), and Neutrons ($n$).
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Spin Precession in $g$-2 Ring
(Top View)

\[ \vec{\omega}_a = -a \frac{e}{m} \vec{B} \]
\[
\mathcal{O} + \mathcal{O} = \mathcal{O}
\]

\[
\left\{ \left( g \times \eta + \frac{\gamma}{n} \right) \frac{v}{u} + \frac{e}{E} \left( \frac{v - 1}{I} \right) + \frac{b}{d} \right\} \frac{m}{\omega} = \mathcal{O}
\]

(at Magic Momentum)
\[
\left( E \times n + E \right) \frac{c}{u} = \omega = \omega
\]

\[
\left\{ \left( E \times n + E \right) \frac{c}{u} + \frac{c}{E \times B} \left( a - I \right) + \frac{m}{\epsilon} \right\} \frac{\omega}{\omega} = \omega
\]

Cancelling E-2 With a Radial E-Field
Parameter Values of Muon EDM Experiment

- Radial E-Field: \( E = \frac{cBa\beta}{1 - (1 + a)\beta^2} \)
  \( E = 2 \text{ MV/m} \)

- Dipole B-field: 1/6 of current value
  \( B \approx 0.24T \)

- Muon Momentum:
  \( P_{\mu} \approx 500 \text{ MeV/c}, \gamma \approx 5 \)
Spin Precession in EDM Ring
(Top View)
\[ \chi^2 = 1.1028, \quad \text{ndf} = 1.199 \]

\[ N_0 = 7.81026 \times 10^6 \pm 3.64891 \times 10^2 \]

\[ \tau_\mu = 1.10051.33 \pm 0.000282 \mu s \]
$\chi^2 = 1.1087, \quad \text{ndf.} = 1.199$

$N_0 = 7.80961 \times 10^6 \pm 3.69917 \times 10^2$

$\tau_\mu = 10.993736 \pm 0.000300 \mu s$
Sensitivity:

\[ d_\mu = \frac{n}{2} \frac{e^h}{2mc} \approx n \times 4.7 \times 10^{-14} \text{ e. cm} \]

Error in \( n \):

\[ \sigma_n = \frac{1}{\gamma T A_1 A \sqrt{2 N_{\text{tot}}}} \]

\( \gamma T = 11 \mu s \)

\( A \): muon decay asymmetry weighted with energy (0.5)

\[ A_1 = \frac{\beta B e}{2 m} \approx 10^8 s \]

\( N_{\text{tot}} \): Total # of detected decays

\[ \sum n \approx 3.5 \times 10^{-11} \text{ for } 1.5 \times 10^{15} \text{ decays} \]

\[ d_\mu \leq 1.5 \times 10^{-24} \text{ e. cm} \]
Modifications:

- Increase Pion/Muon Flux per P.O.T.
- Modify Existing Beamline
- New Inflector (Normal Conducting)
- Use Magnetic (Weak/Strong) Focusing in g-2 Ring
- Flat Radial E-field to Cancel g-2 Precession
- Deuterons as Inclinometer
Increase Pion/Muon Flux per P.O.T.:

- Need to work at Low Muon Momentum

  (Off magic Momentum) of 0.5GeV/c With a Required

  DC Radial Electric Field: \( E = \frac{a B (\gamma^2 - 1)}{\beta} \approx 2 \text{ MV/m} \)

- Pion Momentum: 0.9GeV/c (Select Backward Decay Muons)

- Use Lithium Lens D/S of Target for Pion Focusing
Systematics

- “Vertical” Component of E-field
- De-phasing due to Radial E-field
- Proton or Pion Contamination of Beam (flash)
- Early to Late Counting Effects (Linearity)
- Muon Losses as a Function of Time
- Stored Positrons at Injection
- Horizontal and Vertical Betatron Oscillations Coupling
<table>
<thead>
<tr>
<th></th>
<th>Muon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$10^8$ ($10^{14}$ POT)</td>
<td>$5 \times 10^8$ (dp/p=10^{-4})</td>
</tr>
<tr>
<td>AGS Rep rate</td>
<td>0.4 Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>0.3</td>
<td>0.26</td>
</tr>
<tr>
<td>Interaction Time</td>
<td>50 $\mu$s</td>
<td>5 ms</td>
</tr>
<tr>
<td><strong>Signal</strong> m$\omega t$ ($10^{-24}$ e.cm)</td>
<td>$10^{-7}$ rad</td>
<td>$10^{-6}$ rad</td>
</tr>
<tr>
<td><strong>Background</strong> m$\omega t$ ($10^{-8}$ E)</td>
<td>$10^{-7}$ rad</td>
<td>$7 \times 10^{-5}$ rad</td>
</tr>
</tbody>
</table>
De-phasing of Spin

Radial E-field \( \nu \frac{1}{r} \)

Time \( t = 0 \):
- \( S \rightarrow +2\% \)
- Central momentum
- \( P \rightarrow -2\% \)

\( \mu : \ t = 150\mu s \): 
- \( S \uparrow 90^\circ \rightarrow P \)
- \( P \downarrow 90^\circ \rightarrow S \)
- \( +2\% \)
- \( -2\% \)

\( l : \ 5 ms \)
\( \frac{\Delta P}{P} = 10^{-4} \)
Probing Vertical E-Field Component

- Inject Deuterons-Inclinometer:
  a) Spin Precession vs Time
  b) Vertical Displacement

- Laser Interferometer to Monitor Stability
6 Axis per Laser Head

The Plane mirror interferometers 10706B will measure the change in spacing of the 2 silvered surfaces. The detailed optical layout for all 40 measurement axis is done by the integrator. Other optical components such as Beam Benders 10707A and Adjustable Mounts, 10710A & 10711A, are available to aid in layout and alignment.
Summary

- A New, Sensitive Method of Probing EDM
- Second Generation (Muon)-Very Exciting
- Can Make Use of High Muon Flux