Proposal to measure the muon electric dipole moment with a compact storage ring at PSI

Thomas Schietinger

in collaboration with

K. Kirch, A. Adelmann, A. Streun, G. Onderwater*

*Rijksuniversiteit Groningen

EPFL/LPHE Seminar, 7 February 2007
Contents

• Introduction: lepton dipole moments
• Muon spin precession in $B$ and $E$ fields
• Measurement of $(g-2)_\mu$ at storage rings
• Measurement of $\mu$EDM at storage rings
• A new method to measure $\mu$EDM: the “frozen spin” technique
• Motivations to go below $10^{-19}$ e cm
• A possible layout for PSI
• Sensitivity estimate
• Status of the project
• Summary
Lepton dipole moments

Hamiltonian: \[ \mathcal{H} = -\mu \cdot \vec{B} - d \cdot \vec{E} \]
\[ \mu, d \parallel \vec{\sigma} \]

Define \( g \) and \( \eta \) as unit-free quantities describing magnetic and electric dipole moments, respectively:

\[ \mu = \frac{g}{2} \frac{e \hbar}{2m} \quad d = \frac{\eta}{2} \frac{e \hbar}{2mc} \]

For a Dirac particle (e.g. lepton):
\( g = 2 \) (+ corrections) and
\( \eta = 0 \) (+ super-tiny corrections from CP-violating interactions)

\[ \Rightarrow \text{convenient to define:} \quad \mu = (1 + a) \frac{e \hbar}{2m} \quad a = \frac{g - 2}{2} \]
The importance of lepton $g-2$

- The corrections to $g = 2$ in principle codify all of physics!
- These corrections are more sensitive to physics from higher-mass scales than those to $g_e$ by a factor of $\left(\frac{m_\mu}{m_e}\right)^2 = 42,000$!
- $g_\tau$ even more sensitive, but much harder to measure!
- Therefore biggest effort on measuring and calculating $(g-2)_\mu$.
- A triumph of particle physics! (see later)
(g–2)\(\mu\) contains all of physics!

QED, electroweak, strong,…

... + new physics?

Courtesy L. Roberts and J. Miller
Lepton EDMs

- **EDMs** in elementary particles (also nuclei, atoms and some molecules) **violate P and T symmetries**, therefore **violate CP** if CPT is conserved.
  - No contributions from QED and strong interactions, only higher-order electroweak!

- Current efforts are mainly focused on **neutral particles** (neutron, atoms).
- But lepton EDMs are theoretically **much cleaner**.

\[ \vec{\mu}, \vec{d} \parallel \vec{\sigma} \]

$\eta$ contains almost no physics!

Fourth order electroweak,

Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

... + new physics?

Much greater sensitivity to new physics!
Measuring lepton dipole moments

\( \text{e} \)  Penning Traps / Atomic Physics

Electrons and positrons in Penning traps (MDM); look for T-violation in heavy paramagnetic atoms (EDM)

\( \text{\mu} \)  Storage Rings

Store muons in a ring, observe response to \( E \) and \( B \) fields

\( \text{\tau} \)  Colliders \( \sigma(e^+e^- \rightarrow \tau^+\tau^-)(\sqrt{s}) \)

Exploit dependence of pair production kinematics on dipole moments
Muons spin precession in $B$ field

Muon spin precession in the presence of a uniform $B$ field, perpendicular to the muon momentum:

\[ \vec{\omega}_S = \frac{ge\vec{B}}{2m} + (1 - \gamma)\frac{e\vec{B}}{\gamma m} \]

Larmor precession
(classical)

Thomson precession
(relativistic)

Compare to cyclotron frequency (momentum precession):

\[ \vec{\omega}_C = \frac{e\vec{B}}{\gamma m} \]

Difference: frequency with which the spin precesses relative to the momentum:

\[ \vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = \frac{g - 2}{2} \frac{e\vec{B}}{m} = a_\mu \frac{e\vec{B}}{m} \]

**Gift Nr. 1 from Nature:** get direct access to $a_\mu$ (i.e. $g-2$) by measuring the spin precession relative to the momentum!
Muon spin precession in $B$ and $E$ field

Muon spin precession in the presence of $E$ and $B$ field, perpendicular to each other and to the muon momentum:

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

Example:
$B$-field pointing down, $E$-field radially outward:

$\vec{\omega}_a$: spin precession in orbital plane ("$g$–2" precession)

$\vec{\omega}_e$: spin precession out of orbital plane

$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e$ tilts the precession plane out of the orbital plane
Muon spin precession in $B$ and $E$ field

\[ \vec{\omega} = -\frac{e}{m}\left\{ a\vec{B} + \left(\frac{1}{1 - \gamma^2} - \eta\right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\frac{\vec{E}}{c} + \frac{\vec{\beta} \times \vec{B}}{c}\right)\right\} \]

Strategy for (recent) $g$–2 measurement at storage rings:

- run at “magic $\gamma$”, $\gamma = 29.3$ ($p_\mu = 3.1$ GeV)
  \[ \Rightarrow \text{no effect from electric fields, can use electric focusing} \]
  (need for uniform $B$ field precludes magnetic focusing)
- assume $\eta$ small for measurement of $a$
  \[ \Rightarrow \text{direct access to } a \text{ if } B \text{ is known} \]
- look for small vertical oscillation to put a limit on $\eta$.
  - All recent limits on $\eta$ have been obtained in this way (CERN, Brookhaven)
  - Plagued by systematics: $g$–2 precession interferes strongly!

Gift Nr. 2 from Nature
**g–2 Measurement (E821@Brookhaven)**

A 20-year effort to improve the precision on $a_\mu$ from 7 ppm to 0.5 ppm:

$$a_\mu = 0.001\,165\,920\,80\,(63)$$

![Diagram of electron time spectrum](image)
$g–2$: the most recent state of affairs

$$a_\mu(\text{exp}) = 0.001\ 165\ 920\ 80\ (63)$$

(0.54 ppm)

$$a_\mu(\text{SM}) = 0.001\ 165\ 918\ 04\ (51)$$

(0.44 ppm)

$$a_\mu(\text{exp}) - a_\mu(\text{SM}) = (27.6 \pm 8.1) \times 10^{-10}$$

3.4σ discrepancy!

- New physics or not?
- The deviation is consistent with LHC-accessible SUSY in the few 100 GeV range...
- A proposed upgrade of E821 to halve the error was recently declined (E969).
- Both experiment and theory are at their limits.

For the (beautiful!) history of $g–2$, see:

F.J.M. Farley, Y.K. Semertzidis: The 47 years of muon $g–2$, Prog. Part. Nucl. Phys. 52 (2004) 1

E969:

μEDM at $g-2$ storage rings

- Search for a **vertical oscillation signal** in $g-2$ data (vertical segmentation of some of the electron detectors)

- Seriously limited by two effects:
  1. **$g-2$ rotation** of spin strongly suppresses the effect of $\omega_e$ (spin can be parallel to $\omega_e$ vector!)
  2. **Trajectories** of the decay electrons are very different at the two extremes of vertical oscillation, leading to large systematic effects.

- Best current limit from **Brookhaven E821**:
  \[ d_\mu < 2.4 \times 10^{-19} \text{ e cm} \]
  - Only preliminary, but soon to be published (L. Roberts).
  - Only **modest improvement** with respect to previous (CERN) experiment.

R. McNabb et al.: hep-ex/0407008, unpublished
History of $\mu$EDM measurements

- Berley et al. [1958]
- Berley and Gidal [1960]
- Charpak et al. [1961]
- Bailey et al. [1978]
- McNabb et al. [2004, unpublished]

Stalling progress with conventional storage ring method...
...yet we still have a long way to go!
...yet we still have a long way to go!

A new method is needed!

W. Bernreuther at the Workshop on the Future of Muon Physics, Heidelberg, Germany, May 7–10, 1991:

4 Conclusions

Some popular “non-standard” models of CP violation predict that the muon EDM is not very much bigger than about a few $\times 100d_\mu$. A substantially larger $d_\mu$ is possible in specific versions of left-right symmetric models and leptoquark models. However, if $d_\mu$ is of order $10^{-19} - 10^{-26}$ e cm, one would expect even larger electric and weak dipole form factors of the $\tau$ which should eventually be measurable at LEP. Nevertheless, future experimental determinations of $d_\mu$ will be of interest. It seems also worthwhile to search for experimental methods which would substantially increase the sensitivity to this form factor.

W. Bernreuther:  
The Electric Dipole Moment of the Muon,  
Z. Phys. C 56 (1992) S97
Muon spin precession in \( B \) and \( E \) field

\[
\vec{\omega} = -\frac{e}{m} \left\{ a\vec{B} + \left( \frac{1}{1 - \gamma^2} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\}
\]

New strategy for EDM measurement: the “frozen spin” technique!

- Go to lower momentum, install a “magic \( E \) field” (radially), such that \( \omega_a \) vanishes completely: \( E \approx aBc\beta\gamma^2 \)
  - i.e., return gift Nr. 2 from Nature in exchange for another one!
- The spin remains parallel to the momentum along the orbit (“frozen spin”)
- In the presence of an EDM (\( \eta \neq 0 \)) the spin is slowly rotated out of the orbital plane.
- **Much superior sensitivity** than with parasitic approach!

The “frozen spin” technique

- Turn off the $g-2$ precession with a radial $E$ field
- Up-down detectors measure decay electrons
  - Emission of electrons strongly correlated with spin direction, in particular for high-energy electrons
- Look for an up-down asymmetry, building up **linearly with time**
- Detectors on the inside and outside to measure $g-2$ precession (cross check)

A. Silenko et al.: J-PARC Letter of Intent: Search for the Permanent Muon Electric Dipole Moment at the $10^{-24}$ e cm Level.
J-PARC letter of intent

- Semertzidis, Farley et al. in 2003 proposed an experiment exploiting the frozen spin technique at J-PARC (PRISM-II FFAG).

- Design: 7-m radius ring, with $B = 0.25$ T, $E = 2$ MV/m and $p = 500$ MeV ($\gamma \tau = 11$ µs).

- Estimated sensitivity is around $10^{-24}$ e cm

- So far a “virtual project”, realization not likely before 2015.

Klaus Kirch: could we do this at PSI with lower energy muons?

What is the motivation to go below $10^{-19}$?
Motivations to go below $10^{-19}$ e cm

1) **Model-independent**
   - Ambiguity in $g-2$ measurement
   - Generic new physics based on $g-2$ anomaly

2) **Model-specific**
   - Supersymmetry
   - Left-right symmetric models
   - Any other business model...

3) **Forget about models** altogether: the muon EDM is definitely one of the least tested corners of the SM!
   - Side note: this was the principal motivation for the multi-M$^2$ B-factories – not one theory made a specific prediction for $\sin 2\beta$ (other than the SM)
Ambiguity in $g-2$ measurement?

- The anomalous muon spin precession measured in Brookhaven is usually attributed to new physics in the muon's magnetic dipole moment: $a_{\mu}^{NP} = (27.6 \pm 8.1) \times 10^{-10}$

- But it could just as well arise from new physics in the muon's electric dipole moment: $d_{\mu} = (2.4 \pm 0.4) \times 10^{-19}$ e cm, or a combination of both.

- Current limits are insufficient to resolve the ambiguity.

- Nobody seriously believes that the muon EDM is as large as that...
  - Lee Roberts: “this would have earth-shaking consequences!”

- ...but I could not find anyone who can provide a solid argument as to why it must be smaller!
  - e.g.: “Water would be unstable!”, “Nucleosynthesis would not have worked!”, “Windows 98 would be stable”, or similar.
  - How to quantify “earth-shaking”? 
The $g-2$ anomaly isn't?

J. Feng, T.M. Matchev, Y. Shadmi: 
*The Measurement of the Muon's Anomalous Magnetic Moment Isn't*, 

\[
\omega_{\text{obs}} = \sqrt{\omega_a^2 + \omega_e^2} 
\]

(Updated with latest numbers)
Generic new-physics dipole moment

If one assumes that both non-SM MDM ($a_{\mu}^{\text{NP}}$) and EDM ($d_{\mu}$) are manifestations of the same new-physics object:

$$a_{\mu}^{\text{NP}} \frac{e}{2m_{\mu}} = \Re D \quad \text{and} \quad d_{\mu}^{\text{NP}} = \Im D$$

with $D$ a general dipole operator (W. Marciano),

$$D = |D| \exp(i\phi_{\text{CP}})$$

then the Brookhaven measurement can be interpreted as

$$d_{\mu}^{\text{NP}} = 2.7 \times 10^{-22} \text{e cm} \frac{a_{\mu}^{\text{NP}}}{27.6 \times 10^{-10}} \tan \phi_{\text{CP}}$$

i.e. either $d_{\mu}$ is of order $10^{-22}$ e cm, or the CP phase is strongly suppressed!

Model-specific predictions

- Most reasonable models predict lepton EDMs to scale **linearly with mass**.
  - Strong bound on $d_\mu$ from $d_e < 1.6 \times 10^{-27}$ e cm!

- Some models, however, predict **quadratic** and **cubic** mass scaling
  
- Some SUSY variants can give up to $10^{-22}$ e cm, but this involves a lot of tuning
  - Flavour-violating SUSY a good candidate (but new Belle bound on $\tau \rightarrow \mu \gamma$ probably has a severe impact)

---


A $\mu$EDM experiment at PSI?
Muons at PSI
μE1 beamline and area

Existing infrastructure

Muon “beam”:
- ~400 π mm mrad emittance
- ~10^8 μ^+ / s
- Bunch width 3.9 ns FWHM

For comparison:
my car

I.C. Barnett et al.:
also: http://ltp.web.psi.ch
Concept for an experiment at PSI

Apply \textbf{frozen spin technique} at \textbf{lower energy} than J-PARC proposal:

- PSI $\mu$E1: $p_\mu = 125$ MeV ($\beta = 0.76$, $\gamma = 1.55$), $P_\mu = 92\%$
- Choose $B = 1$ T (conventional magnet, straightforward change of polarity)
  $\Rightarrow$ 42 cm orbit radius, radial $E$-field 0.64 MV/m (64 kV across 10 cm gap).

Trade off high intensity of muon beam for \textbf{beam quality}, selecting the muons to be injected into the ring:

- Reduce from 100 MHz to $\sim 200$ kHz
- One muon at a time! Measurement time $\approx \gamma \tau_\mu = 3.4 \mu$s.
- Assume run-time of $2 \times 10^7$ s, times 200 kHz gives $4 \times 10^{12}$ muon decays (per year)
- Clockwise and counter-clockwise operation (systematics)
µE₁ beamline and area

For comparison:
my car

A ~1-m-diameter storage ring with support fits in comfortably
Main challenges

- **Injection**
  - Cannot use conventional kicker due to very short turn-around time (12 ns)
  - Possible solution: *resonance injection* at half-integer tune using a non-linear field perturbator (inflector)

- **Injection trigger**
  - Minimal latency between detection of “good muon” and ramp-up of inflector

- **Detector**
  - $B$-field, limited space, systematics issues

- **Data processing / storage**
  - $O(10^{12})$ muon decays, almost all of them carry interesting information!
Resonance injection method

- Developed for injection into commercial **tabletop synchrotron light-sources**
  - AURORA series (50 cm orbit radius), MIRROCICLE (15.6 cm!) by Photon Production Laboratories, Ltd.
  - [http://www.photon-production.co.jp/](http://www.photon-production.co.jp/)

- **Perturbator** excites half-integer betatron resonance (e.g. 3/2), decay to stable orbit over several turns

H. Yamada: 

H. Yamada: 

H. Yamada et al.: 
Injection study for $\mu$EDM project

- Andreas Adelmann, using TRACY program
  
  http://slsbd.psi.ch/pub/slsnotes/tmeta9902/

- 20 turns ramp of non-linear perturbator

- Acceptance $\pm 7$ mm / $\pm 11$ mrad, average latency for acceptable $\mu$: $\sim 1.2$ $\mu$s

- Average measurement time $\gamma \tau_{\mu} = 3.4$ $\mu$s

- $\sim 200$ kHz repetition rate for perturbator
  
  - Challenging, in particular for “random” ramp-up
  
  - Can we trigger the perturbator in time to catch the “good” muon?
Beam schematic

- Pions produced in thick target
- Capture muons from *backward* decay of pions ⇒ polarized muons ($P_\mu = 92\%$)
- Upon “good muon”-trigger, inflector ramps down non-linear perturbation field over a period of 20 turns
- Resonance injection at half-integer
Detector

- Identifies direction of decay $e^\pm$ (at least up- or downwards)
- Energy resolution helps (at least low energy cutoff)
- Full reconstruction nice but probably not necessary (some segmentation in $\theta$, $\phi$, $z$)
- Timing below 1 ns desirable (at least 10 ns)
- Limited space and $B$-field will be challenging!
- RooFit toy Monte Carlo study in progress to study requirements in detail.
- Full GEANT4 simulation of a possible detector setup in preparation

Technology so far completely open!
Various systematics issues...

- **Vertical $E$ field** component: $E_\perp < 10^{-4} E_{\text{rad}}$.  
  - Most dangerous: local vertical $E$ field components
- Rotational **misalignments** and residual $g$–2 precession
- **Instabilities** of $E$, $B$ fields, detector,...

...but many ways to control them:

- Injection of $\mu^+$ and $\mu^-$
  - Factor 3 less statistics for $\mu^-$
- Clockwise and counter-clockwise orbit
- $g$–2 precession for calibration
- Spin rotation?

Sensitivity estimate

Uncertainty on \( \eta \) from a simple asymmetry counting experiment with \( N \) decays:

\[
d_\mu = \frac{\eta}{2} \frac{e\hbar}{2m_\mu c} \simeq \eta \times 4.7 \times 10^{-14} \text{ e cm}
\]

\[
\sigma_\eta = \frac{\sqrt{2}}{\gamma\tau(e/m)\beta B A P \sqrt{N}}
\]

\( A \) : electron asymmetry, assume \( A = 0.3 \)
\( P \) : polarization of muons

J-PARC proposal: \( \gamma\tau = 11 \mu s, \beta = 0.978, P = 50\%, B = 0.25 \text{ T} \)

\[
\Rightarrow \sigma_\eta = 4 \times 10^{-3}/\sqrt{N}; \quad N = 4 \times 10^{16} \Rightarrow \sigma_\eta = 2 \times 10^{11}
\]

\[
d_\mu < 10^{-24} \text{ e cm}
\]

PSI proposal: \( \gamma\tau = 3.4 \mu s, \beta = 0.76, P = 90\%, B = 1.0 \text{ T} \)

\[
\Rightarrow \sigma_\eta = 2.4 \times 10^{-3}/\sqrt{N}; \quad N = 4 \times 10^{12} \Rightarrow \sigma_\eta = 10^{-9}
\]

\[
d_\mu < 5 \times 10^{-23} \text{ e cm}
\]

Muon statistics is the dominant factor!
Impact of a PSI measurement

- Rule out EDM explanation for Brookhaven MDM anomaly
- Rule out (or confirm) naïve relation between new physics MDM and EDM for the case $\phi_{CP} \approx 1$.
- Explore the region down to $5 \times 10^{-23}$ e cm
- ... long before J-PARC (or anyone else) can get there.
Workshop on
Precision Measurements at Low Energy
Future Particle Physics Research at PSI
18.–19.01.2007 at the
Paul Scherrer Institut, Villigen, Switzerland

Review speakers
• D. Dubbers, Heidelberg
• W. Henning, Darmstadt
• G. Hermann, Heidelberg
• K. Jungmann, Groningen
• Y. Kuno, Osaka
• H. Rauch, Wien
• S. Paul, München
• L. Roberts, Boston
• S. Schönert, Heidelberg
• N. Severijns, Leuven
• C. Weinheimer, Münster

Poster presentation
Poster contributions are highly welcome and will be a central part of the meeting. We call for presentation of new ideas and projects in astro-particle, ultracold neutron, lepton flavor and nuclear physics as well as concerning new accelerators and high power target stations. Deadline for submissions is December 20th, 2006.

Organizing committee
• H. Gäggeler, Bern & PSI
• R. Eichler, PSI & ETHZ
• A. Rubbia, ETHZ
• K. Kirch, PSI
• A. van Loon, PSI

Information: ltp.web.psi.ch
Registration: anita.vanloon@psi.ch
Current status of the project

• **Poster presentation** at PSI workshop was **met with enthusiasm:**
  - C. Petitjean: “the highlight of the workshop”
  - K. Jungmann: “for just 0.25% of its annual budget, PSI could have a **profound impact on muon physics**”

• **Strong interest** to participate from **Boston University** (Lee Roberts) and **Groningen** (Gerco Onderwater) “once the project gets going”.

• Paper presenting the compact storage ring method in more detail is in preparation.

• Next steps:
  - Look for **interested parties**, in particular at **Swiss Universities**!
  - With a larger proto-collaboration, can envisage writing a **letter of intent** for the next PSI user meeting (early 2008).
Summary

- **A great opportunity to do fundamental particle physics at PSI**
  - When was the last time you could push a fundamental parameter by four orders of magnitude?

- **Project involves exciting detector *and* accelerator development**
  - A unique opportunity for close collaboration between LPHE and LPAP within IPEP!

- **Joining now means designing a complete experiment from scratch!**

\[ d_\mu < 5 \times 10^{-23} \text{e cm} \]