Muon $g-2$ and EDM Experiments of the Muon, Deuteron, and Neutron.

Yannis K. Semertzidis
Brookhaven National Lab

• Muon $g-2$ experiment
• EDMs: What do they probe?
• Physics of Hadronic EDMs
• Experimental Techniques
**Definition of g-Factor**

\[
g \equiv \frac{e\hbar / 2mc}{\text{angular momentum}}
\]

\[
g \equiv \frac{e\hbar / 2mc}{\hbar}
\]

\(g-2\) measures the difference between the charge and mass distribution. \(g-2=0\) when they are the same all the time…

From Dirac equation \(g-2=0\) for point-like, spin \(\frac{1}{2}\) particles.

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
**g-factors:**

- Proton ($g_p = +5.586$) and the neutron ($g_n = -3.826$) are composite particles.
- The ratio $g_p/g_n = -1.46$ close to the predicted $-3/2$ was the first success of the constituent quark model.
- The experimental sensitivity of $g_e^{-2}$ (electron) due to quantum field fluctuations involving only QED.
- The $g_{\mu}^{-2}$ is more sensitive to a class of particles than the $g_e^{-2}$ by $(m_{\mu}/m_e)^2 \approx 40,000$. 

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
$g - 2$ for the muon

Largest contribution: \[ a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800} \]

Other standard model contributions:

- QED
- hadronic
- weak
Theory of $a_\mu$

- $a_\mu(\text{theo}) = a_\mu(\text{QED}) + a_\mu(\text{had}) + a_\mu(\text{weak})$
  $+ a_\mu(\text{new physics})$

- $a_\mu(\text{QED}) = 11 658 470.6 \ (0.3) \times 10^{-10}$
- $a_\mu(\text{had}) = 694.9 \ (8.) \times 10^{-10}$ (based on $e^+e^-$)
- $a_\mu(\text{had}) = 709.6 \ (7.) \times 10^{-10}$ (based on $\tau$)
- $a_\mu(\text{weak}) = 15.4 \ (0.3) \times 10^{-10}$

- $a_\mu(\text{SM}) = 11 659 181(8) \times 10^{-10}$ (based on $e^+e^-$)
- $a_\mu(\text{SM}) = 11 659 196(7) \times 10^{-10}$ (based on $\tau$)
Experimental Principle:

• Polarize: Parity Violating Decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

• Interact: Precess in a Uniform B-Field

• Analyze: Parity Violating Decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
The Principle of $g$-2

Spin vector  Non-relativistic case

\[ \omega_c = \frac{eB}{m} \]

\[ \omega_s = \frac{g}{2} \frac{eB}{m} \]

\[ \omega_a = \omega_s - \omega_c = \frac{g}{2} \frac{eB}{m} - \frac{eB}{m} = \left( \frac{g - 2}{2} \right) \frac{eB}{m} \Rightarrow \omega_a = a \frac{eB}{m} \]

\[ \frac{d\vec{s}}{dt} = \vec{\bar{\mu}} \times \vec{B} + \vec{\bar{d}} \times \vec{E} \]

Yannis Semertzidis, BNL
Spin Precession in g-2 Ring  
(Top View)

\[ \vec{\omega}_a = a \frac{e}{m} \vec{B} \]

Momentum vector
Spin vector
Effect of Radial Electric Field

- Low energy particle
- ...just right
- High energy particle

\[ \frac{d\hat{s}}{dt} = \hat{\mu} \times \hat{B} + \hat{d} \times \hat{E} \]
Effect of Radial Electric Field

- …just right, $\gamma \approx 29.3$
- for muons
  ($\sim 3\text{GeV/c}$)

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
• The Muon Storage Ring: $B \approx 1.45T$, $P_\mu \approx 3$ GeV/c

• High Proton Intensity from AGS
Detectors and vacuum chamber
Energy Spectrum of Detected Positrons

Flavour at LHC era, 7 November, 2005
Yannis Semertzidis, BNL
4 Billion $e^+$ with $E>2\text{GeV}$

$$dN / dt = N_0 e^{-\frac{t}{\tau}} [1 + A \cos (\omega_a t + \phi_a)]$$
Theory and Experiment vs. Year

Flavour at LHC era, 7 November, 2005

Yannis Semertzidis, BNL

\[ \frac{d\bar{s}}{dt} = \bar{\mu} \times \bar{B} + \bar{d} \times \bar{E} \]

Error: 0.5ppm, Statistics dominated

Experiment  Theory
Comparison of CMD2 data with KLOE

Plotted is \[ \frac{\Delta F}{F} = \frac{|F_{\pi}|^2 \text{ (exp)}}{|F_{\pi}|^2 \text{ (CMD-2 fit)}} - 1 \]

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Future measurements at VEPP-2000

- Factor >10 in luminosity
- Up to 2 GeV c.m. energy
- CMD-3: major upgrade of CMD-2 (new drift chamber, LXe calorimeter)
- Measure $2\pi$ mode to 0.2-0.3%
- Measure $4\pi$ mode to 1-2%
- Overall improvement in $R$ precision by factor 2-3

Under construction. Data taking is expected to start is 2007-2008.
New g-2 Proposal at BNL

• Increase Beamline acceptance (×4)

• Open up the two Inflector ends (×1.7)

• Use Backward Muons (i.e. π @ 5.3GeV/c, μ @ 3.1GeV/c). Provides great π-Rejection.

• Reduce systematics both in ω_a and in B
Prospects and Summary
See talk by G. Onderwater on Wednesday, WG3

• Total experimental error (statistics dominated): 0.5ppm; probing physics beyond the S.M.

• More data ($\times 10$) from the theory front are being analyzed: Novosibirsk, KLOE, BaBar, Belle.

• The g-2 collaboration is working towards reducing the experimental error to 0.2ppm. The proposal at BNL received scientific approval (E969) in 2004 and in Spring 2006 it is going to P5 (a US national committee); funding approval is pending from DOE.
EDM: Particles with Spin…

For a particle with a spin, only the EDM component along the spin survives.

\[ \vec{d} = 0 \]

\[ \vec{d} \propto d \hat{\sigma} \]

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
A Permanent EDM Violates both $T$ & $P$ Symmetries:

$$\frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}$$
A Permanent EDM Violates both $T$ & $P$ Symmetries:

$$H = -d \tilde{\sigma} \cdot \tilde{E} \quad \xrightarrow{T} \quad H = -d(-\tilde{\sigma}) \cdot \tilde{E} = d\tilde{\sigma} \cdot \tilde{E}$$

$$H = -d \tilde{\sigma} \cdot \tilde{E} \quad \xrightarrow{P} \quad H = -d\tilde{\sigma} \cdot (-\tilde{E}) = d\tilde{\sigma} \cdot \tilde{E}$$

\[ \frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E} \]
How about Induced EDMs?

\[ \vec{d} \sim d\vec{E} \]

\[ H = -d\vec{E} \cdot \vec{E} \quad \text{OK} \]

\[ H = -d\vec{E} \cdot \vec{E} \quad \text{OK} \]

\[ H = -d\vec{\sigma} \cdot \vec{E} \quad \text{1st order Stark effect. T, P Violation!} \]

\[ H = -d\vec{E} \cdot \vec{E} \quad \text{2nd order Stark effect. Allowed!} \]

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
MDMs are Allowed…

\[ H = -\mu \vec{\sigma} \cdot \vec{B} \quad \xrightarrow{T} \quad H = -\mu (-\vec{\sigma}) \cdot (-\vec{B}) = -\mu \vec{\sigma} \cdot \vec{B} \]

\[ H = -\mu \vec{\sigma} \cdot \vec{B} \quad \xrightarrow{P} \quad H = -\mu (\vec{\sigma}) \cdot (\vec{B}) = -\mu \vec{\sigma} \cdot \vec{B} \]

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{a} \times \vec{E} \]
Andrei Sakharov 1967:

\[ \frac{n_B}{n_\gamma} \approx 10^{-9} \]

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....
EDM Searches are Excellent Probes of Physics Beyond the SM:

Most models beyond the SM predict values within the sensitivity of current or planned experiments:

• SUSY
• Multi-Higgs
• Left-Right Symmetric …
EDM in an Electric Field…

\[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}
\]

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
Precession of a Top in a Gravitational Field

\[ \omega = \frac{mgl}{L}, \quad \vec{L} = I \vec{S} \]

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Usual Experimental Method

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]

Compare the Zeeman Frequencies When E-field is Flipped:

\[ \hbar (\omega_1 - \omega_2) = 4dE \]

\[ \sigma_d \propto \frac{1}{E} \frac{1}{\sqrt{N \tau T}} \]
Neutron EDM Vs Year

“...at $6 \times 10^{-26}$ e cm, it is analogous to the Earth's surface being smooth and symmetric to less than 1 µm” (John Ellis).
UW $^{199}$Hg EDM Limit — Historical Perspective


## EDM Status

<table>
<thead>
<tr>
<th>Particle</th>
<th>System</th>
<th>Limit [e·cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$^{205}$Tl ($\sim 10^{-24}$ e·cm)</td>
<td>$1.5 \times 10^{-27}$</td>
</tr>
<tr>
<td>Mercury</td>
<td>$^{199}$Hg atom</td>
<td>$2 \times 10^{-28}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>Ultra-Cold n</td>
<td>$5 \times 10^{-26}$</td>
</tr>
<tr>
<td>Proton</td>
<td>$^{199}$Hg atom</td>
<td>$5 \times 10^{-24}$</td>
</tr>
</tbody>
</table>
Prospects of neutron EDM:

• **UCN at PSI**: Ramsey’s method of separated oscillatory fields. First goal $1 \times 10^{-27} \text{e} \cdot \text{cm}$, begin data taking ~2007. See talk by Klaus Kirch on Tuesday, WG3.

• **UCN at ILL (Sussex, RAL, …)**: Ramsey’s method of separated oscillatory fields. Goal $2 \times 10^{-28} \text{e} \cdot \text{cm/year}$, begin data taking 2009. Plamen Iaydjiev, Tuesday, WG3.

• **Ultra-Cold Neutrons (UCN), at SNS (LANL, …)**: Polarized $^3\text{He}$ stored together in a superfluid $^4\text{He}$. Goal $1 \times 10^{-28} \text{e} \cdot \text{cm}$, begin data taking ~2011.
UCN tank system (5 m high)

UCN storage volume
2m³

UCN shutter

p beam

D₂O moderator

solid D₂ moderator

spallation target

T_p = 600MeV
I_p = 2mA
10n/p
Per pulse:
10¹⁷p → 10¹⁸n
thermal flux:
2•10¹⁴ s⁻¹ cm⁻²
cold flux:
2•10¹³ s⁻¹ cm⁻²
UCN:
2•10⁶ s⁻¹ cm⁻³
3•10³ cm⁻³ stored
UCN experiment at ILL:
Expect a factor of $\sim 100$ improvement in sensitivity due to

- Neutrons in 0.5 K He bath
- $\sim 50 \times$ more neutrons
- E-field: $4-6 \times$ at cryo temp.
- Longer coherence times
Neutron EDM at SNS. Aiming at $1 \times 10^{-28} e \cdot cm$, begin construction 2007, begin data taking 2011

Proposed Experimental Design
Concept for HV generator

Q = CV

Variable capacitor in LHe volume

500 kV

50 kV
SUPERFLUID HELIUM AS A DETECTOR

Superfluid $^4$He filled chamber

$$n + ^3\text{He} \rightarrow p + t + 764 \text{ kV}$$

The energetic charged particles produced excited state helium molecules, $^*\text{He}_2$

The excited state decays in a few nsec (triplet) and produces 80 nm light for which the superfluid helium is transparent.

The 80 nm light is converted to 450 nm (visible) that can be detected by a photomultiplier tube. Approximately 1 photon/keV deposited is produced.

6/16/03

NI$\text{SA}$

Physics

Los Alamos
$^3\text{He}$-DOPANT AS AN ANALYZER

$^3\text{He} + n \rightarrow t + p \quad \sigma(\text{parallel}) < 10^2 \text{ b}$

$\sigma(\text{opposite}) \sim 10^4 \text{ b}$

UCN loss rate $\sim$

$1 - p_3 \cdot p_n = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)B_0 + 2dE]t$

$\frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}$
Hadronic EDMs

\[ L_{\varphi} = \varphi \frac{\alpha_s}{8\pi} GG \]

\[ d_n(\varphi) - d_p(\varphi) \leq 3.6 \times 10^{-16} \varphi \text{ e} \cdot \text{cm} \rightarrow \varphi \leq 2 \times 10^{-10} \]

Why so small? Axions? Cern Axion Solar Telescope…

CP-violation at RHIC!! (preliminary) Nucl-ex/0510069

Centrality of Collisions

\[ \frac{d\hat{s}}{dt} = \hat{\mu} \times \hat{B} + \hat{d} \times \hat{E} \]
Deuteron EDM

\[ d_D = (d_n + d_p) + d_D^{\pi NN} \]

\[ d_D (\bar{\theta}) \square -10^{-16} \bar{\theta} \text{ e} \cdot \text{cm} \]

i.e. @ 10^{-29} e\cdot cm: \[ \bar{\theta} \leq 10^{-13} \]
A value of $\theta_{QCD} = 10^{-13}$ would create an EDM of

<table>
<thead>
<tr>
<th>System</th>
<th>EDM value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>$\approx 3 \times 10^{-29} e \cdot \text{cm}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$\approx -3 \times 10^{-29} e \cdot \text{cm}$</td>
</tr>
<tr>
<td>Deuteron</td>
<td>$\approx 1 \times 10^{-29} e \cdot \text{cm}$</td>
</tr>
<tr>
<td>Tl atom</td>
<td>$\approx 5 \times 10^{-31} e \cdot \text{cm}$</td>
</tr>
<tr>
<td>Hg atom</td>
<td>$\approx 1 \times 10^{-32} e \cdot \text{cm}$</td>
</tr>
</tbody>
</table>
Quark EM and Color EDMs

\[ L_{CP} = -\frac{i}{2} \sum_{q} \bar{q} \left( d_q \sigma_{\mu\nu} F^{\mu\nu} + d_q^c \sigma_{\mu\nu} G^{\mu\nu} \right) \gamma_5 q \]

\[ d_D \left( d_q, d_q^c \right) = 0.5 \left( d_u + d_d \right) - 5.6e \left( d_u^c - d_d^c \right) - 0.2e \left( d_u^c + d_d^c \right) \]

\[ d_n \left( d_q, d_q^c \right) = 0.7 \left( d_d - 0.25d_u \right) + 0.55e \left( d_d^c + 0.5d_u^c \right) \]

i.e. Deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…

Flavour at LHC era, 7 November, 2005

Yannis Sextos
Sensitivity to SUSY models

$d$ EDM at $\sim 10^{-29} \text{e} \cdot \text{cm}$

$n$ EDM at $\sim 10^{-28} \text{e} \cdot \text{cm}$

Sensitivity to right-handed $\nu_\tau$ mass

Hadronic EDMs in SUSY SU(5) GUTs with right-handed neutrinos

Junji Hisano $^a$, Mitsuru Kakizaki $^a$, Minoru Nagai $^a$, Yasuhiro Shimizu $^b$

$^a$ ICRR, University of Tokyo, Kashiwa 277-8582, Japan
$^b$ Department of Physics, Tohoku University, Sendai 980-8578, Japan

“The supersymmetric grand unified models (SUSY GUTs) are ones of the well-motivated models after discovery of the gauge coupling unification at the LEP experiment. Non-vanishing light neutrino masses shown in the neutrino oscillation experiments might also suggest existence of the SUSY GUTs since the right-handed neutrino masses expected from the measurements are near the GUT scale in the seesaw mechanism [1]. Nowadays many efforts are devoted to search for the next signature from both theoretical and experimental sides.”

\[
\frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}
\]
CEDMs for the down quark vs $M_{N3}$

Neutron sensitivity at $10^{-28}$ e·cm

Deuteron sensitivity at $10^{-29}$ e·cm

$= \bar{\mu} \times \bar{B} + \bar{d} \times \bar{E}$
Experimental Methods of Storage

Ring Electric Dipole Moments

• Parasitic to g-2
• Frozen spin
• Resonance

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Electric Dipole Moments in Storage Rings

\[ \frac{d\vec{s}}{dt} = \vec{d} \times (\vec{u} \times \vec{B}) \]

e.g. 1T corresponds to 300 MV/m for relativistic particles

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Indirect Muon EDM limit from the g-2 Experiment

\[ \vec{\omega} = \frac{e}{m} \left\{ a\vec{B} + \frac{\eta}{2c} \left( \vec{u} \times \vec{B} \right) \right\} \]

\[ \vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm} \]

\[ \tan \theta = \frac{\omega_{edm}}{\omega_a} \]

Ron McNabb’s Thesis 2003: \(< 2.7 \times 10^{-19} \text{ e} \cdot \text{cm} \> \text{ 95\% C.L.}\)

Flavour at LHC era, 7 November, 2005

Yannis Semertzidis, BNL

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
The Vertical Spin Component Oscillates due to EDM

Vertical Spin Component a.u.

$0 \mu s \rightarrow g-2$ period $\rightarrow 8 \mu s$
Effect of Radial Electric Field

- Low energy particle
- ...just right
- High energy particle

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]

Yannis Semertzidis, BNL
Use a Radial Electric Field and a

- Low energy particle

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Spin Precession in g-2 Ring
(Top View)

\[ \vec{\omega}_a = \alpha \frac{e}{m} \vec{B} \]

Momentum vector
Spin vector

Flavour at LHC era, 7 November, 2005
Yannis Semertzidis, BNL

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Spin Precession in EDM Ring
(Top View)

$\mu$

Momentum vector

Spin vector

$\vec{\mathcal{W}}_a = 0$

$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$
(U-D)/(U+D) Signal vs. Time

Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, versus time.
Muon EDM Letter of Intent to
J-PARC/Japan, 2003

J-PARC Letter of Intent: Search for a Permanent Muon
Electric Dipole Moment at the $10^{-24}$ e⋅cm Level.

A. Silenko, Belarusian State University, Belarus
R.M. Carey, V. Logashenko, K.R. Lynch, J.P. Miller†, B.L. Roberts
Boston University
G. Bennett, D.M. Lazarus, L.B. Leipuner, W. Marciano,
W. Meng, W.M. Morse, R. Prigl, Y.K. Semertzidis†
Brookhaven National Lab
V. Balakin, A. Bazhan, A. Dudnikov, B. Khazin, I.B. Khriplovich, G. Sylvestrov
BINP, Novosibirsk
Y. Orlov, Cornell University
K. Jungmann, Kernfysisch Versneller Instituut, Groningen
P.T. Debevec, D.W. Hertzog, C.J.G. Onderwater, C. Ozben
University of Illinois
E. Stephenson, Indiana University
M. Auzins, University of Latvia
P. Cushman, Ron McNabb, University of Minnesota
N. Shafer-Ray, University of Oklahoma
K. Yoshimura, KEK, Japan
M. Aoki, Y. Kuno#, A. Sato, Osaka, Japan
M. Iwasaki, RIKEN, Japan
F.J.M. Farley, V.W. Hughes, Yale University
January 9, 2003

†Spokesperson
# Resident Spokesperson
Expected Muon EDM Value from $a_\mu$

\[
L_{DM} = \frac{1}{2} \left[ D \bar{\mu} \sigma^{\alpha\beta} \frac{1 + \gamma_5}{2} + D^* \bar{\mu} \sigma^{\alpha\beta} \frac{1 - \gamma_5}{2} \right] \mu F_{\alpha\beta},
\]

where $\sigma^{\alpha\beta} = \frac{1}{2} [\gamma^\alpha, \gamma^\beta]$ and

\[
a_\mu \frac{e}{2m_\mu} = \Re D,
\]

\[
d_\mu = \Im D,
\]

\[
D^{SUSY} = |D^{SUSY}| e^{i\phi_{CP}}
\]

\[
d_\mu = 2 \times 10^{-22} \text{ e} \cdot \text{cm} \frac{a_\mu^{SUSY}}{25 \times 10^{-10}} \tan(\phi_{CP})
\]

Flavour at LHC era, 7 November, 2005

Yannis Semertzidis, BNL

\[
\frac{d\tilde{s}}{dt} = \bar{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}
\]
\[ \vec{\omega} = \frac{e}{m} \{ a\vec{B} + \frac{\eta}{2c} (\vec{u} \times \vec{B}) \} \]

\[ \vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm} \]

\[ \tan \theta = \frac{\omega_{edm}}{\omega_a} \]
Vertical Spin Component **without** Velocity Modulation (deuterons)
Vertical Spin Component with Velocity Modulation at $\omega_a$
Vertical Spin Component with Velocity Modulation (longer Time)
Velocity (top) and $g$-2 oscillations

A new idea by Yuri Orlov!

Particle velocity oscillations

Particle $S_L$ oscillations (i.e. $g$-2 oscillations)

The synchrotron oscillation phase (top) compared to $g$-2 phase (bottom). ~5us total horizontal scale $\frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}$
Yuri Orlov’s new lattice

Flavour at LHC era, 7 November,
Systematic errors due to AC forces

• AC forces, due to modulating $v$ at $\omega_a$.

Examples: 1) Radial B-field or skew quadrupole where $D \neq 0$, 2) RF-cavity (vertical offset or misalignment), …

• Remedy: They depend on the vertical tune… They all do!
AC Backgrounds are vertical tune dependent; EDM signal is not!

\[ \frac{ds_v}{dt} \propto \frac{1}{Q_v^2 - Q_s^2} \]
Two half beam technique

This tune makes the Deuteron spin more sensitive to background.

\[ \frac{d\hat{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Storage Ring Electric Dipole Moments

- $D @ 10^{-29}e\cdot cm$ would be the best EDM sensitivity over *present* or *planned* experiments for $\theta_{QCD}$, quark, and quark-chromo (T-odd Nuclear Forces) EDMs.

- $P$, $D$, $^3He$, etc., i.e. a facility to pin down the CP-violation source.
Deuteron EDM Timeline

• ~end of this year/January 2006 Letter of Intent

• We need to develop the final ring lattice and tolerances on parameters

• Goal for a proposal by the end of next year
## Neutron/deuteron EDM Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Exp begin sens. data taking</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>UCN-PSI</td>
<td>$10^{-27} \text{e}\cdot \text{cm}$</td>
</tr>
<tr>
<td>2009</td>
<td>UCN-ILL</td>
<td>$2 \times 10^{-28} \text{e}\cdot \text{cm/yr}$</td>
</tr>
<tr>
<td>2010</td>
<td>Deuteron in Storage Ring</td>
<td>$10^{-29} \text{e}\cdot \text{cm}$</td>
</tr>
<tr>
<td>2011</td>
<td>UCN-LANL/SNS</td>
<td>$1 \times 10^{-28} \text{e}\cdot \text{cm}$</td>
</tr>
</tbody>
</table>

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
Summary

• Neutron, and deuteron EDM experiments are sensitive probes of physics beyond the SM and of CP-violation in particular.

Unique sensitivity to

• $\theta_{\text{QCD}}$
• Quark EDM
• Quark-color EDM

Both n and deuteron EDM exp: pinpoint EDM source

Promising a very exciting decade…!
Extra Slides

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]
Ed Stephenson’s

**IDEA:**
- make thick target defining aperture
- scatter into it with thin target

**Alternative way: resonant slow extraction (Y. Orlov)**

- "extraction" target - ribbon
- Target could be Ar gas (higher Z).
- Target "extracts" by Coulomb scattering deuterons onto thick main target. There's not enough good events here to warrant detectors.
- Hole is large compared to beam. Everything that goes through hole stays in the ring.
- Detector is far enough away that doughnut illumination is not an acceptance issue: $\Delta < R$.

$\frac{d\hat{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$
List of things to do...

1. Compaction factor: $\alpha_p = 1$ or $\alpha_p \neq 1$  Graziano Venanzoni, and Yuri Orlov

2. Low beta (=0.6) Super-Conducting Cavities with one mode having $\omega = 3 \omega_{RF}$  Alberto Facco, ...

3. Space Charge, Impedance, etc.  Mikhail Zobov

4. RFQ

5. Polarimetry M.C.  Anna Ferrari, Ed Stephenson

6. Slow Extraction together with polarimetry

7. Spin Coherence Time  Yuri Orlov

8. Sextupoles, Decapoles, how many needed?  Y.O.

$\frac{d\vec{s}}{dt} = \vec{u} \times \vec{B} + \vec{d} \times \vec{E}$
RF-fields and oscillation phases

E-field in RF-cavity

B<sub>R</sub>-field in RF-cavity

Particle velocity oscillations

Particle S<sub>L</sub> oscillations (g-2)

\[ \frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E} \]
Other Issues


\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
Ramsey’s method

"Spin up" neutron...

Apply π/2 spin flip pulse...

Free precession.

Second π/2 spin flip pulse.

\[ \frac{d}{dt} = \mu \times B + d \times E \]
Hadronic contribution to muon \((g-2)\)

Hadronic contribution to the muon \((g-2)\) is calculated via dispersion integral:

\[
a^\text{had} \mu (l.o.) = \left( \frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{s_\infty} ds \frac{K(s)}{s^2} R(s)
\]

Contribution to the integral from different modes \(e^+e^- \to \) hadrons:

\(e^+e^- \to 2\pi\) gives dominant contribution both to the value and to the uncertainty of the hadronic contribution

\[
\frac{ds}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}
\]
CMD-2 Result

Flavour at LHC era, 7 November, 2005

Yannis Semertzidis, BNL

\[
\begin{align*}
|F_\pi|^2 &= \mu + \bar{B} + \bar{d} \times \bar{E} \\
\text{Energy, MeV} &\quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \\
\text{Systematic error} &\quad 0.7\% \quad 0.6 \div 0.8\% \quad 1.2-4.2\%
\end{align*}
\]
Beyond standard model, e.g. SUSY

\[ a_{\mu}^{\text{susy}} \equiv \text{sgn}(\mu) \times 13 \times 10^{-10} \left( \frac{100 \text{GeV}}{m_{\text{susy}}} \right)^2 \tan \beta \]

SUSY, dark matter, \((g-2) \Delta_{E821}\)

\[ \Delta a_\mu(\text{E821} - \text{SM}) = (23.9 \pm 9.9) \times 10^{-10} \]

Present \(\Delta\)

\(\tan \beta = 10, \mu > 0\)

\(m_h = 114 \text{ GeV}\)

\(m_{\chi^\pm} = 104 \text{ GeV}\)

\(\Omega h^2 = 0.09\) (WMAP)

\(\Omega h^2 = 0.12\)

\(g-2\) 2\(\sigma\)

Excluded for neutral dark matter

\(\text{CMSSM} \) (constrained minimal supersymmetric model)

\(\frac{d\tilde{s}}{dt} = \tilde{\mu} \times \tilde{B} + \tilde{d} \times \tilde{E}\)
Future Comparison: $\Delta_{E969} = \Delta_{\text{now}}$

Present $\Delta$, future error $\tan \beta = 10$, $\mu > 0$

$m_{h} = 114$ GeV

$m_{\chi^{\pm}} = 104$ GeV

$\Delta_{g-2}$ 1σ

following Ellis Olive, Santoso Spanos

(Provided by K. Olive)
Future Comparison: $\Delta_{E969} = 0$

$\Delta=0$ Future error

$\tan \beta = 10, \mu > 0$

$m_h = 114$ GeV

$m_{\chi^\pm} = 104$ GeV

Historically $(g-2)$ has played an important role in restricting models of new physics.

following Ellis Olive, Santoso, Spanos

(Provided by K. Olive)