The Proposal for a Dedicated Experiment to Measure the Deuteron and Muon EDMs

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Outline

- Introduction
- Theory predictions: muon and deuteron
- EDM Measurements with Storage Rings

  Previous measurements: muon EDM in g-2 experiments

  Proposed new approach: freeze MDM spin precession in a ring
- Plans
- Conclusions

Electric Dipole Moments

- Non-zero permanent EDM violates T and P symmetries
- With CPT invariance, T violation $\rightarrow$ CP violation

  Source of CP violation in K's, B's not understood

  New sources of CP violation needed: e.g. to explain matter-antimatter asymmetry
- Current EDM experimental limits are *far* larger than SM predictions

  Non-zero EDM $\rightarrow$ New Physics

Current Experimental Limits on EDMs

$d_n = -1.0 \pm 3.6 \times 10^{-26} e \cdot cm$, $< .63 \times 10^{-25} e \cdot cm$ (90% CL)

SM: $< 10^{-31}$

$d_p = 3.7 \pm 6.3 \times 10^{-23}$

$d(^{199}Hg) = -1.06 \pm 0.49 \pm 0.40 \times 10^{-28}$, $< 2.1 \times 10^{-28}$ (95% CL)

$d_e = 0.69 \pm 0.74 \times 10^{-27}$, $< 1.6 \times 10^{-27}$ (90% CL) SM: $< 10^{-38}$

$d_\mu = 3.7 \pm 3.4 \times 10^{-19}$, $< 1.1 \times 10^{-18}$ (90% CL) SM: $< 10^{-35}$

(CERN III Statistical: $\pm 2.7 \times 10^{-19} e \cdot cm$, Systematic: $\pm 2 \times 10^{-19} e \cdot cm$)

Proposed Measurement of the Muon's Electric Dipole Moment

New experiment goal: $\sigma_{d_\mu} \approx 10^{-24} \rightarrow > 10^5$ improvement

- With conventional scaling,
  $d_\mu = \frac{m_\mu}{m_e} d_e = 1.4 \pm 1.5 \times 10^{-35}$, $< 3.3 \times 10^{-25}$ (90% CL).
  -predicted by SM and some of simplest theories, e.g. MSSM with assumption of universality of scalar masses, proportionality of A terms.
- Not hard to get non-conventional scaling in supersymmetry:
  e.g. $d_\mu \approx$ few $\times 10^{-23}$
  -Babu, Dutta, Mohapatra, PRL 85, 5064(2000): L-R symmetric w/seesaw mechanism + large neutrino mixing, $d_\mu \approx 5 \times 10^{-23} e \cdot cm$, $d_e \approx 10^{-28} \approx 10\times$ less than current expt. limit.
- A number of theories predict $d_\mu > 10^{-24}$
- Only accessible EDM outside first generation
- d_μ: crucial to understanding nature of the source of EDM.

General dipole moment operator

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

$$a_\mu = \frac{2m_\mu}{e} ReD, \quad d_\mu = ImD$$

Define $D^{NP} = |D^{NP}|e^{i\phi_{CP}}$, $\quad a_{NP} = a_\mu^{exp} - a_\mu^{SM}$,

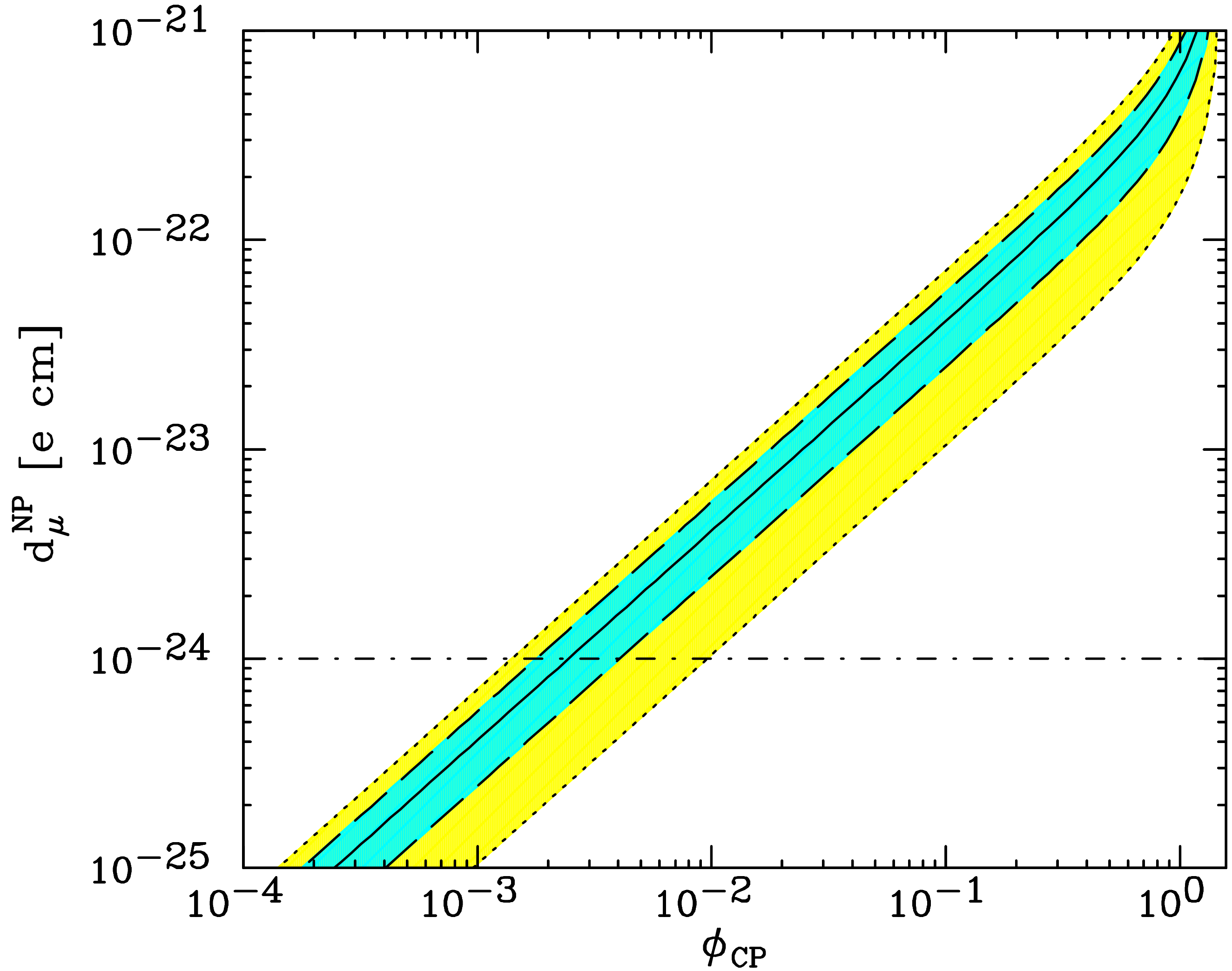
'New Physics' will induce an EDM:

$d_\mu^{NP} \approx 3 \times 10^{-22} (\frac{a_\mu^{NP}}{3\times 10^{-9}}) \tan\phi_{CP} \; e \cdot cm$

$a_{NP} = a_\mu^{exp} - a_\mu^{SM} \approx 3(1) \times 10^{-9} \rightarrow d_\mu^{NP} \approx 3 \times 10^{-22} \tan\phi_{CP} \; e \cdot cm$

$d_\mu \approx 10^{-24} \; e \cdot cm$ probes $|\tan\phi_{CP}| > 3(1) \times 10^{-3}$

Alternatively, $|a_{NP}| =< 1 \times 10^{-9}$ gives $|a_\mu^{NP} \tan\phi_{CP}| < 10^{-11} \; e \cdot cm$



$d_\mu^{NP} \approx 3\times10^{-22}(\frac{a_\mu^{NP}}{3\times10^{-9}}) \tan\phi_{CP}\ e\cdot cm$, $a_{NP} = a_\mu^{exp} - a_\mu^{SM} \approx 3(1)\times10^{-9}$

Feng, Matchev, Shadmi, NP B613, 366(2001)

Using Storage Rings to Measure EDM of Deuteron

New experiment goal: $\sigma_{d_{deut}} \approx 10^{-26}\ e \cdot cm$

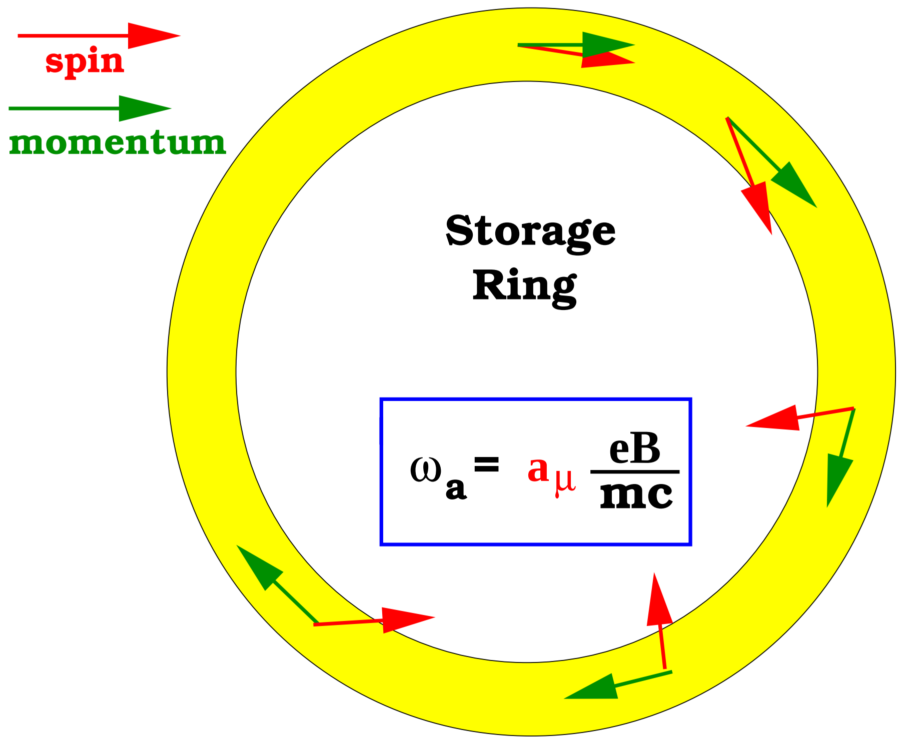
- Potential sources of EDM:
  neutron, proton, P- and T- odd nuclear force
- Nuclear physics is fairly straightforward
- For EDM(deuteron) $\approx 10^{-25}$:
  Competitive with current limits on P,T odd nuclear force from neutron and ^{199}Hg (40 times more sensitive to P, T odd nuclear force than neutron, no Schiff suppression of nuclear EDM as in ^{199}Hg)
  (*Khriplovich and Korkin*)

Using Storage Rings to Measure EDMs

I. Methods used in previous muon g-2 expts at CERN and BNL

II. Proposed new method for a dedicated EDM Expt.

g-2:
Simplified picture
No $\vec{E}$
No EDM



(exaggerated ~20x)

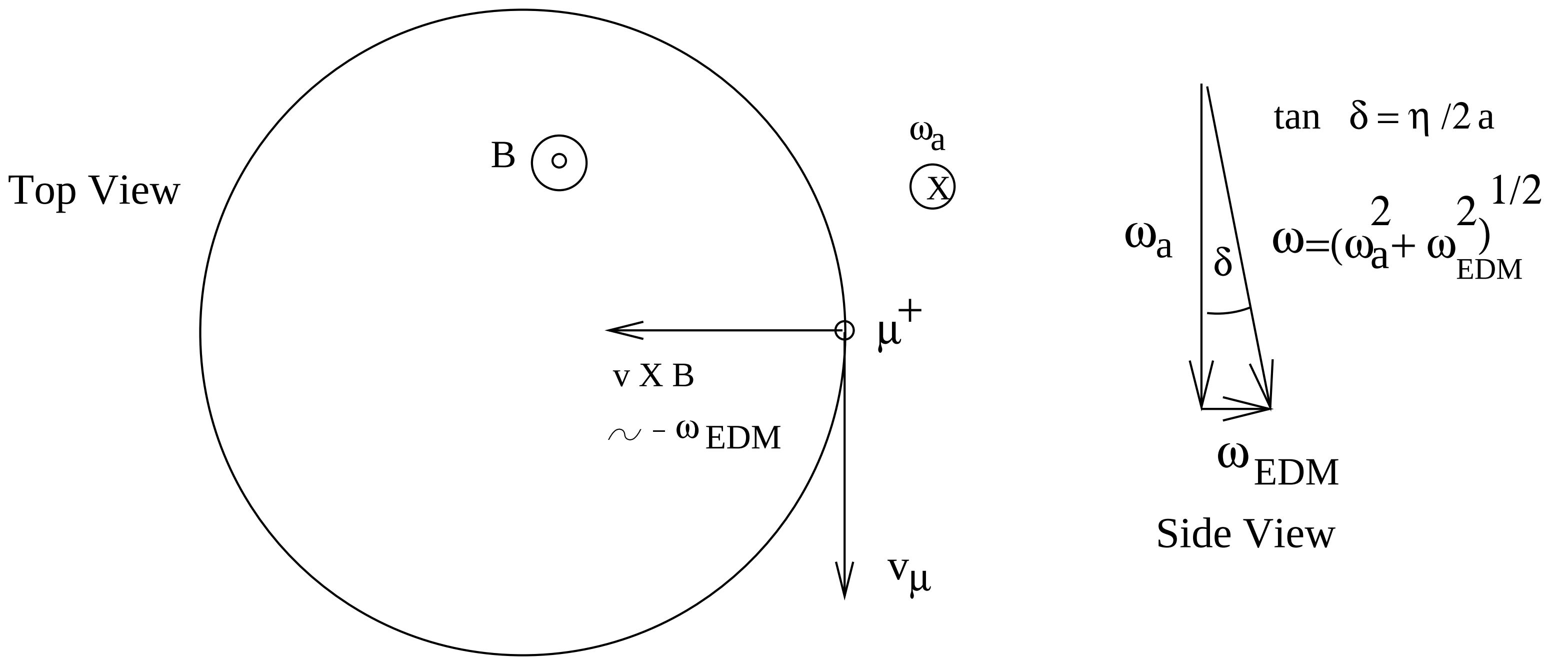
Measurement of Muon EDM in (g-2) Experiments

Spin Precession with $\vec{B}$ and $\vec{E}$ and an EDM (assume planar motion)

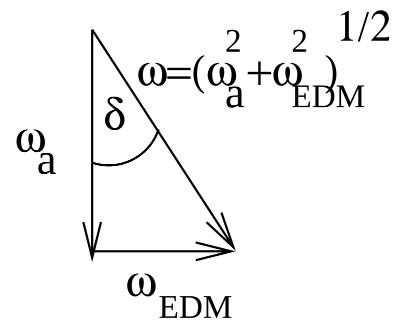
$$\vec{\omega} = -\frac{e}{m}[a_\mu \vec{B} + (-a_\mu + \frac{1}{\gamma^2 - 1})\vec{\beta} \times \frac{\vec{E}}{c} + \frac{\eta}{2}(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c})]$$

where MDM$=(1 + a_\mu)(\frac{e\hbar}{2m})$, EDM $= d_\mu = \frac{\eta}{2}(\frac{e\hbar}{2mc})$

For g-2 experiments: Choose γ so that $-a_\mu + \frac{1}{\gamma^2-1} \approx 0$



Methods Used by CERN III, BNL g-2 Expts.



- Method I. *Assume* discrepancy with SM, $\Delta\omega = \omega - \omega_{SM}$, is due entirely to d_μ rather than to a_μ.

  $\omega = \sqrt{\omega_{SM}^2 + \omega_{EDM}^2} \rightarrow \omega_{EDM} = \sqrt{\omega^2 - \omega_{SM}^2} \approx \sqrt{2\omega\Delta\omega}$

  (Since $d_\mu \approx 0$ in SM, $\omega_{SM} = \omega_{a_\mu,SM}$)

  -Worked well for CERN: large $\frac{\sigma_{a_\mu}}{a_\mu} = 7ppm$, a_μ consistent w/ SM

  -Not as well suited to BNL g-2 expt: small $\frac{\sigma_{a_\mu}}{a_\mu} = .7ppm$, a_μ NOT consistent with SM within errors, SM value currently unstable at that accuracy.

- Method II. Tipping of $\vec{\omega}$ away from vertical in radial direction

  $$\tan\delta = \frac{\eta}{2a_\mu} \quad \alpha \quad d_\mu$$

  $\rightarrow p_{z(avg)}$ of decay electrons oscillates at frequency ω $\rightarrow$oscillation in average vertical position of electrons at the detector vs time (both proportional to d_μ)

Method II: Up-Down Oscillation of Decay Electrons

$R_N = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, $N_{up,down}$ = # electrons above,below mid-plane

CERN III: $d_\mu = 3.7 \pm 3.4 \times 10^{-19}\ e \cdot cm$, $\delta = \frac{\omega_{EDM}}{\omega_a} \approx .5 \times 10^{-2}$

Systematic Issues

- Vertical misalignment between beam and detector vertical centroids + spin dependence of vertical width of electron dist. at detectors → false EDM signal.

  Correct by aligning detectors with centroid of oscillations in vertical mean of electrons caused by horizontal betatron oscillations of beam
- Detector tilt
- Energy calibration of detectors
- Timing offsets

BNL g-2: Anticipate improvement of x3-5 over CERN III, i.e. $\sigma \approx 1 \times 10^{-19}$ with equal Stat. and Syst. errors.

The Muon EDM Collaboration

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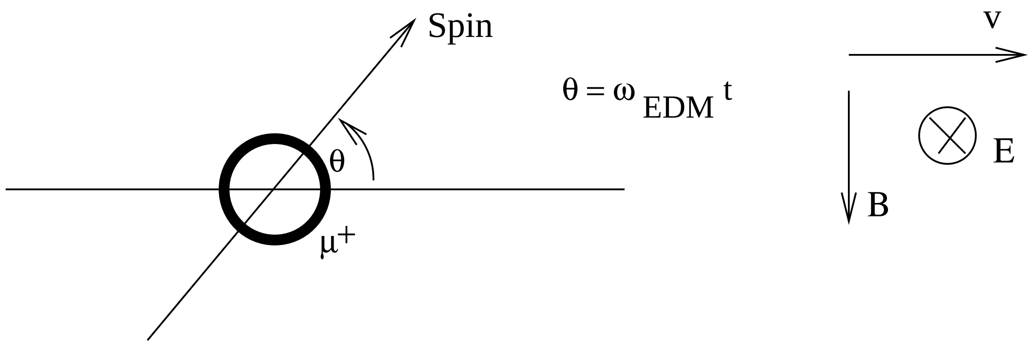
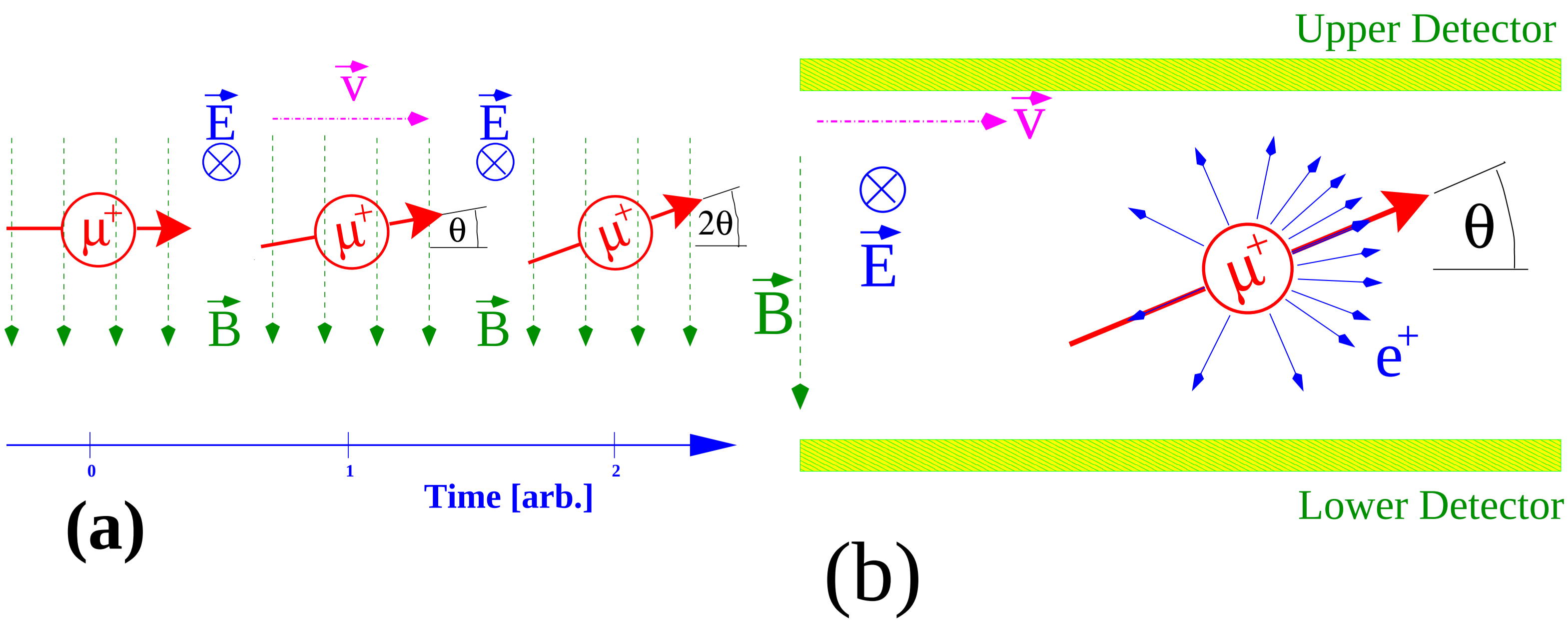
New Approach for Dedicated EDM Experiment

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

- Choose γ, $\vec{B}$ and $\vec{E}$ so that precession due to first two terms sums to zero: $E_r = \frac{a_\mu c B_z}{(\frac{1}{\gamma^2-1} - a_\mu)\beta_\theta} \approx a_\mu B c \beta \gamma^2$, $E_z = 0$, $B_r = B_\phi = 0$
- Leaves only precession due to EDM: $\omega_{EDM} = -\frac{e}{m}\frac{\eta}{2}(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B})$
  Result: Large enhancement of EDM signal relative to g-2 precession background, precession directed radially.
  (Before: $\delta \approx 10^{-2}$ New method: $\theta \approx 1$ after 1τ)
- Focus beam with gradient B-field





Signals

Muons: $R_N(t) = \frac{N_{up}(t) - N_{down}(t)}{N_{up}(t) + N_{down}(t)}$ or $R_E(t) = \frac{E_{up}(t) - E_{down}(t)}{E_{up}(t) + E_{down}(t)}$

Deuterons: $R_N(t) = \frac{N_{right}(t) - N_{left}(t)}{N_{right}(t) + N_{left}(t)}$

Statistical error on EDM

$$\sigma_d = \frac{\hbar}{2\sqrt{2}\gamma\tau v BAP\sqrt{N}} = \frac{\hbar m}{2\sqrt{2}\tau p BAP\sqrt{N}}$$

m =mass, p =momentum, $P =$ polarization, $A =$ asymmetry of vertical decays, $N =$ number of detected electrons, $\tau =$ lifetime (muon, 2.2μs), or coherence time (deuteron=1 s), B=B-field.

To minimize statistical error

- Maximize $P\sqrt{N}$, B, p
- Subject to constraint on $\vec{B}$, $\vec{E}$, γ: $E_r = \frac{a_\mu B_z}{(\frac{1}{\gamma^2-1} - a_\mu)\beta_\theta} < 2\ MV/m$

For $B = 0.25T$, $p \approx 0.5\ GeV/c$

Muon: $\sigma_{d_\mu} = 10^{-24} e \cdot cm,\ A = 0.3,\ P = 0.4, \rightarrow$ $N \approx 4 \times 10^{16}$ With PRISM-II, available from J-PARC in one year of running.

Deuteron: $\sigma_{d_d} = 10^{-26} e \cdot cm,\ A = 0.4,\ P = 0.6, \rightarrow$ $N \approx 2 \times 10^{11}$, 20 kHz on detectors, 5×10^8 deut/s for 10^7 s.

Potential Systematic Error Due to Non-planar $\vec{E}$

Recall $\vec{\omega} = -\frac{e}{m}[a_\mu \vec{B} + (-a_\mu + \frac{1}{\gamma^2-1})\vec{\beta} \times \frac{\vec{E}}{c} + \frac{\eta}{2}(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c})]$

$$\vec{\omega}_{EDM} = -\frac{e\eta}{2m}(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}) = -\frac{e\eta}{2m}(\beta B_z + \frac{E_r}{c})\vec{e}_r \quad \alpha \quad \vec{F}$$

$$< F_z >= 0 \rightarrow \beta_\theta B_r = \frac{E_z}{c}$$

Sum of first two terms in $\vec{\omega}$ causes false EDM signal (e.g. spin precession about a radial axis) due to non-zero values for B_r and E_z:

$$(a_\mu \vec{B} + (-a_\mu + \frac{1}{\gamma^2-1})\vec{\beta} \times \vec{E}) = (a_\mu B_r + (-a_\mu + \frac{1}{\gamma^2-1})\beta_\theta E_z)\vec{e}_r$$

$$\approx \frac{E_z}{\beta_\theta \gamma^2}\vec{e}_r$$

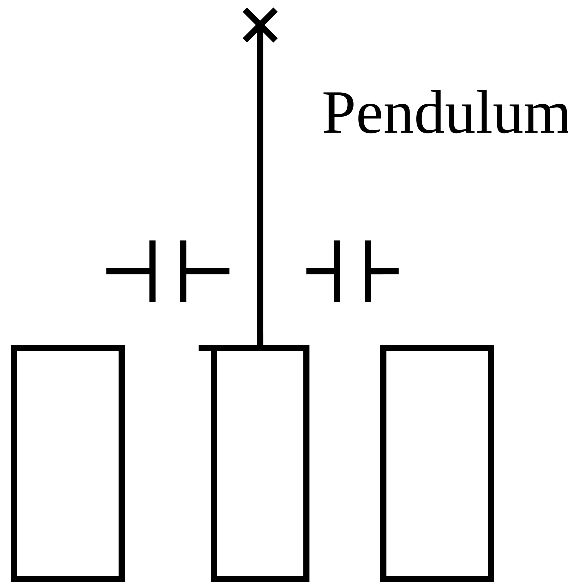
Largest potential source of systematic error

Handling the non-planar E-field

Requirement: $< E_z > \approx 0 \rightarrow \vec{E}$ aligned in a plane to 10 nR.

In practice:

- Align $\vec{E}$ electrodes then monitor with inclinometers



- Inject muons CW and CCW in ring (B_z changes sign, B gradient and E_r do not change sign)
  EDM precession flips sign, $< E_z >$ (false) precession does not.

Systematic Error from Detectors and Stored Beam Instability

Muons

$$R_E(t) = \frac{E_{up}(t) - E_{down}(t)}{E_{up}(t) + E_{down}(t)}$$

Deuterons

$$R_N(t) = \frac{N_R(t) - N_L(t)}{N_R(t) + N_L(t)}$$

Main issues: gain stability vs. time, beam position movement vs. time

CW and CCW storage will cancel effect.

Muons: Left-right counters monitor beam stability, precession

Deuterons: Up-down counters monitor beam stability, precession, give T_{21} correction (next slide)

Systematic error from T_{21} term in deuteron

Deuteron scattering cross-section:

$$\sigma(\theta) = \sigma_0(\theta)[1 + \sqrt{3} p_z \sin\beta \cos\phi \; iT_{11}(\theta) + \frac{1}{2\sqrt{2}} p_{zz} (3\cos^2\beta - 1) T_{20}(\theta)$$

$$+ \sqrt{3} p_{zz} \sin\beta \cos\beta \sin\phi \; T_{21}(\theta) - \frac{\sqrt{3}}{4} p_{zz} \sin^2\beta \cos 2\phi \; T_{22}(\theta)]$$

$\theta =$ scattering angle, $\hat{y}$ perpendicular to scattering plane

Spin direction: spherical coordinates, β = polar angle from beam direction, ϕ = azimuth from $\hat{y}$, p_z = vect pol., p_{zz} = tensor pol.

For scattering in the horizontal plane,

- EDM causes β to increase linearly with time at $\phi = 0$
- MDM causes β to increase linearly with time at $\phi = \frac{\pi}{2}$

Plan

Remarkably, similar ring setup for both Muons and Deuterons!

E-field needed to cancel ω_a: $E \approx Bcp(a\frac{\gamma}{m})$

For $p \approx 500\ MeV/c$,

Muon: $a = 0.001166$, $\gamma \approx 5$, $m = 0.105\ GeV/c$, $a\frac{\gamma}{m} = 0.054$

Deuteron: $a = -0.143$, $\gamma \approx 1$, $m = 1.876\ GeV/c$, $a\frac{\gamma}{m} = -0.076$

Similar design principles apply to both μ and d EDM rings

- Storage ring

  $E \approx 2MV/m$, B$\approx .25T$, $p \approx 500MeV/c$

  Strong magnetic focusing

  Inject CW and CCW to control systematic errors
- Studies under way to increase applied E-field- especially feasible for small aperture (deuteron)
- Polarized, pulsed, high flux sources

  Muons: J-PARC, 1 year running

  Deuterons: KVI (Netherlands), Indiana U, BNL, 1 year running
- Develop detectors

  Muons: calorimeters for decay electrons, very high rates

  Deuterons: Scattering target plus polarimeter, left-right scintillators
- Time scale: Proposal $<$ 1 year? J-PARC letter of intent already submitted, deuteron site review under way

Proposed EDM ring- Preliminary Design

$p = 0.5$ GeV/c

$B_z = 0.25$ T

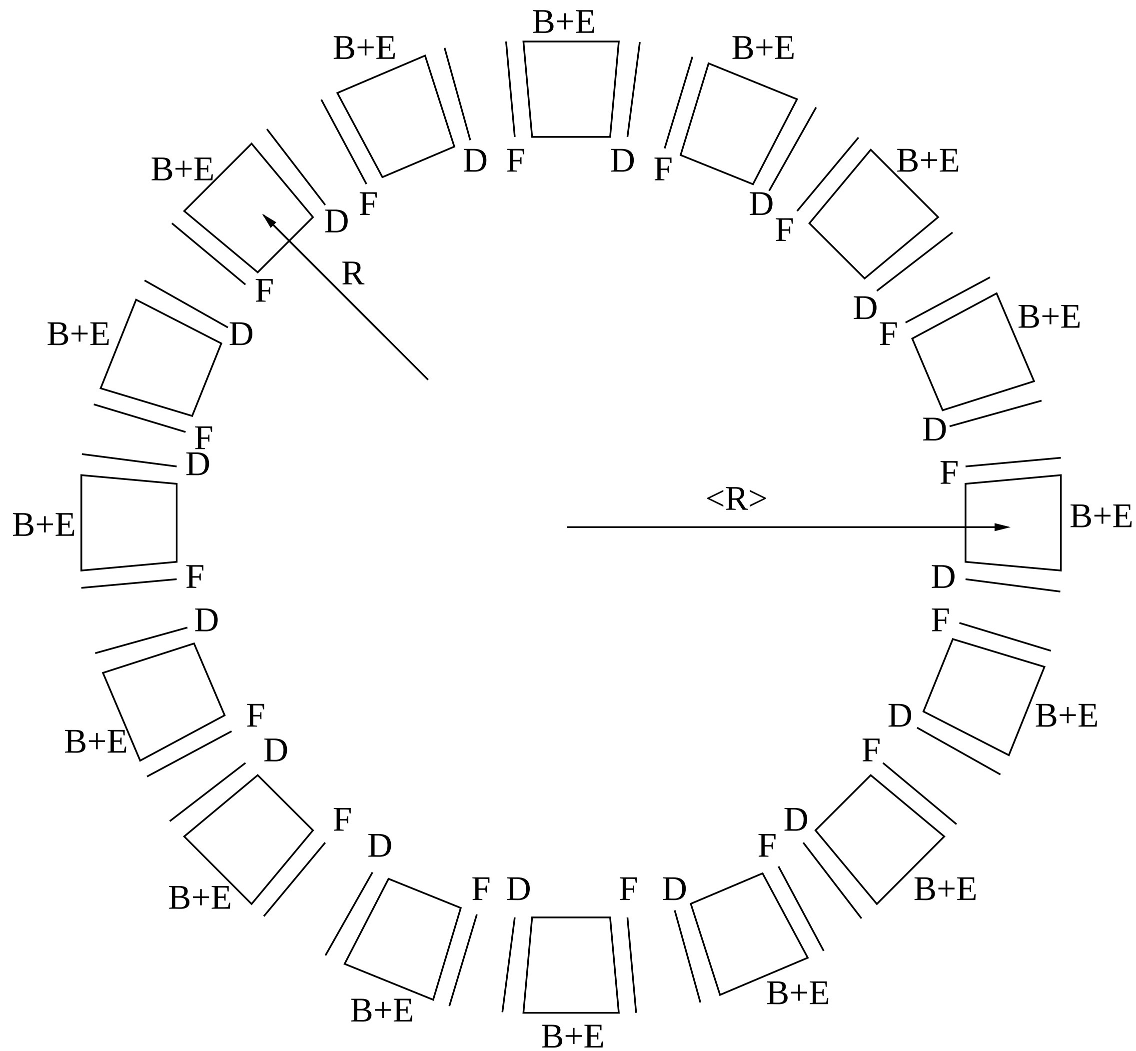
$E_r = 2$ MV/m

$R = 7$ m

$< R >= 11$ m

B+E= 2.6 m

Intervals= 1.7 m



Proposed PRISM-II muon Beam Line

- Pion capture: High-field solenoid: B=6 T, r=10 cm x L=120 cm
- Semi-adiabatic transfer to lower solenoid field: B=6 T $\rightarrow$ 1 T, r=10cm-45 cm x L=450 cm
- Pion momentum selection (curved solenoid) B=1T, r=45cm x R=5 m, arc =50^0
- Pion decay and muon transport: B=1 T, r=45 cm x L=20 m
- Muon momentum selection
- Muon momentum compression: Fixed Field Alternating Gradient phase rotator

  normal version: B=1.8 T, r=21 m

  superconducting version: B=2.8 T, r=10 m

  $\frac{\Delta p}{p} = 30\% \rightarrow 2\%$

Conclusions

- Both $d_\mu \approx 10^{-24}\ e \cdot cm$ and $d_d \approx 10^{-26}\ e \cdot cm$ have significant physics reach
- New technique of freezing MDM in a storage ring shows much promise
- J-PARC has the potential to provide the needed muon flux ($\approx$ 2007-8) (LOI submitted)
- KVI, Indiana, BNL all have potential to supply pulsed polarized deuterons (Site evaluation under way)
- Studies will continue toward full proposals