Recent Results and Progress on Leptonic and Storage Ring EDM Searches: EDM searches in proton, electrons, and muons

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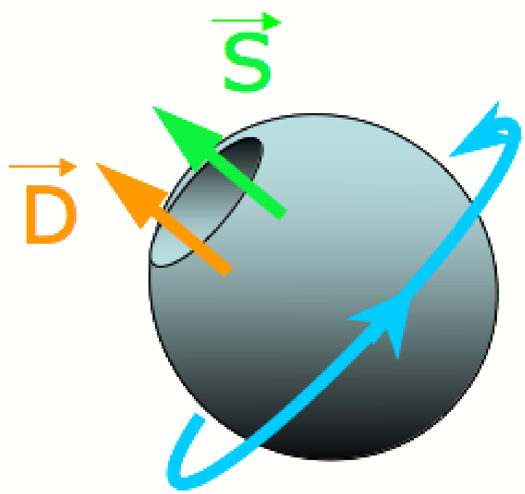


What is a Permanent Electric Dipole Moment (EDM) ?

- Non-relativistic interactions of bare spin 1/2 particle with magnetic moment $\vec{\mu}$ and EDM $\vec{d}$

$$H_{\text{Magnetic Dipole}} = -\vec{\mu}\cdot\vec{B} \;=\; -\,\mu\vec{\sigma}\cdot\vec{B}$$

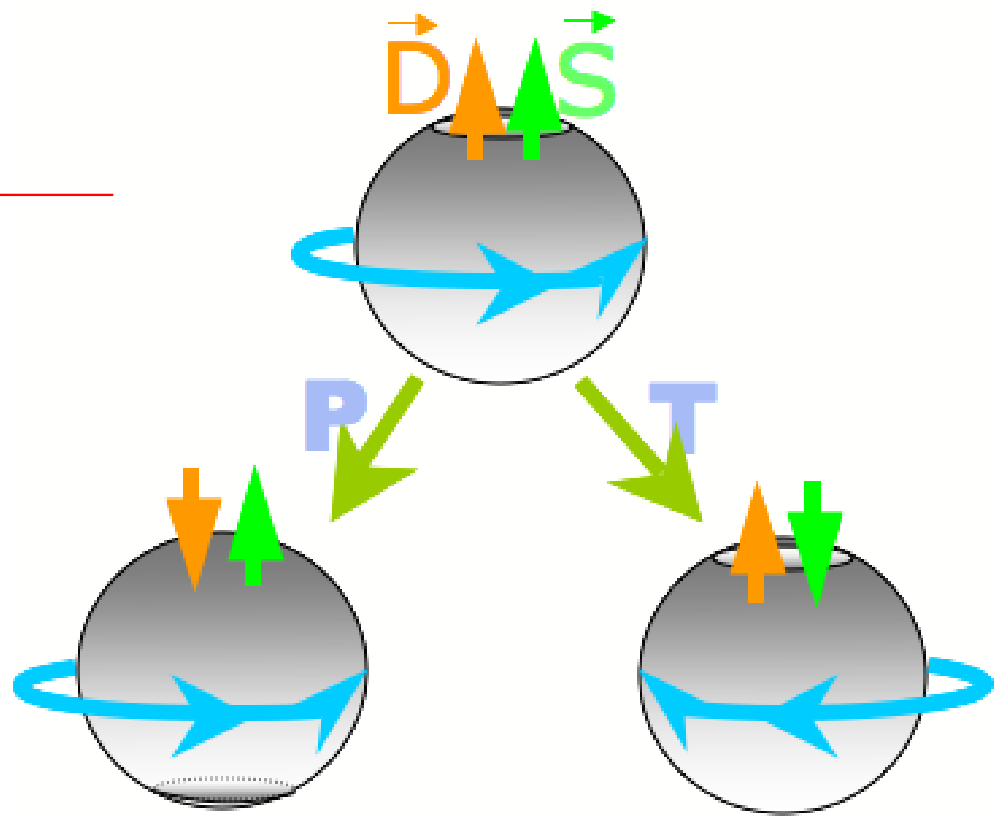
$$H_{\text{Electric Dipole}} = -\vec{d}\cdot\vec{E} \;=\; -\,d\vec{\sigma}\cdot\vec{E}$$

- EDM is analog of magnetic dipole moment
- Manifests itself as a linear Stark effect

Behavior of Moments under Parity and Time Reversal

	$\vec{\sigma}\sim\vec{r}\times\vec{p}$	$\vec{B}\sim\vec{j}\times\vec{r}/\lvert\vec{r}\rvert^3$	$\vec{E}\sim-\vec{\nabla}V$
P	even	even	odd
T	odd	odd	even

- $H_{\text{Magnetic Dipole}}$ is P-even and T-even
- $H_{\text{Electric Dipole}}$ is P-odd and T-odd !!!



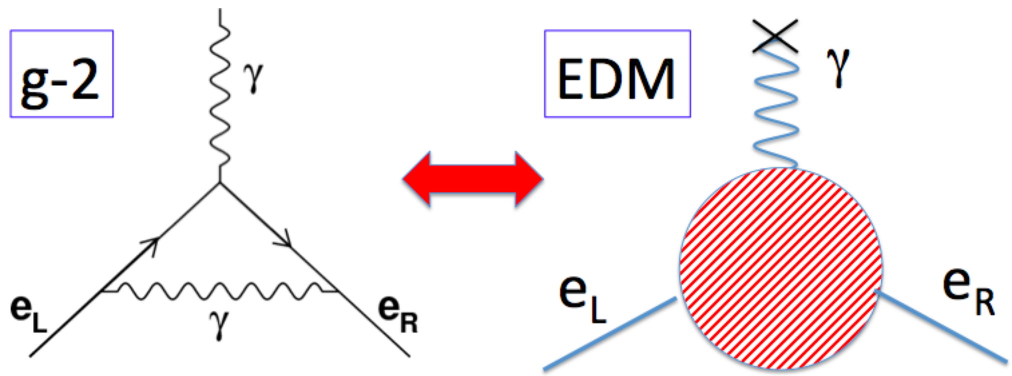
⇒ For fundamental particle to have an EDM, P and T must be violated

Why do we expect the electron, proton, neutron, nucleus ... EDMs $d \neq 0$?

- EDMs violate P, T : through CPT theorem T-violation $\Leftrightarrow$ CP-violation
- P-violation observed, CP-violation observed in K and B mesons
- Can generate EDM using Standard Model physics through radiative corrections

$\Rightarrow$ In same way radiative corrections make $g_{e,\mu} \neq 2.0000$, RC can make $d_{e,\mu} \neq 0$

$\Rightarrow$ Construct diagram with enough loops to incorporate P and CP-violating processes



- In SM need at least 4 loops - predicts $|d_e| \leq 1 \times 10^{-38}$ e·cm
- Well below incredibly impressive current limit $|d_e| < 8.7 \times 10^{-29}$ e·cm !

(J. Baron *et al.* (ACME Collaboration), "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron", Science **343** (6168), 269 (2014))

- Reference scale "dipole moment" of a molecule $\approx e \times a_0 \approx 5 \times 10^{-9}$ e·cm

Current limits on electron, proton, neutron, nuclear EDMs

⇒ There is no evidence for a non-zero permanent electric dipole moment of a fundamental particle, despite searching since the 1950s : Should we give up?

Particle/Atom	SM value [e·cm]	Current EDM Limit	d_n equivalent
Neutron	$\approx 10^{-32} - 10^{-31}$	$< 2.9 \times 10^{-26}$	2.9×10^{-26}
^{199}Hg		$< 3.1 \times 10^{-29}$	5.8×10^{-26}
^{129}Xe		$< 6 \times 10^{-27}$	6×10^{-23}
Proton	$\approx 10^{-32} - 10^{-31}$	$< 7.9 \times 10^{-25}$	7.9×10^{-25}
Deuteron	$\approx 10^{-32} - 10^{-30}$		
Electron	$\approx 10^{-40} - 10^{-38}$	$< 8.7 \times 10^{-29}$	

Neutron Limits : C.A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)

Mercury Limits : W.C. Griffiths *et al.*, Phys. Rev. Lett. **102**, 101601 (2009).

Electron Limits : J. Baron *et al.* (ACME Collaboration), Science **343** (6168), 269 (2014).

Current and Future limits on electron, proton, neutron, nuclear EDMs

⇒ There is no evidence for a non-zero permanent electric dipole moment of a fundamental particle ⇒ but there may be soon !

Particle/Atom	SM value [e·cm]	Current EDM Limit	Future Goal	d_n equivalent
Neutron	$\approx 10^{-32} - 10^{-31}$	$< 2.9 \times 10^{-26}$	10^{-28}	10^{-28}
^{199}Hg		$< 3.1 \times 10^{-29}$	10^{-29}	2×10^{-26}
^{129}Xe		$< 6 \times 10^{-27}$	$10^{-30} - 10^{-33}$	$10^{-26} - 10^{-29}$
Proton	$\approx 10^{-32} - 10^{-31}$	$< 7.9 \times 10^{-25}$	10^{-29}	10^{-29}
Deuteron	$\approx 10^{-32} - 10^{-30}$		10^{-29}	$3 \times 10^{-29} - 5 \times 10^{-31}$
Electron	$\lesssim 10^{-40}$	$< 8.7 \times 10^{-29}$	$10^{-29} - 10^{-31}$	

Some Current and Future Experimental Efforts

Electron EDM	Hadronic EDMs
Cs Trap : Penn. St., UTexas	Ultracold Neutrons : SNS, ILL, PSI, Munich
Cs Fountain : LBNL	^{199}Hg Cell : Seattle/Princeton
PbO Cell : Yale	^{129}Xe Cell : Tokyo Inst. of Tech.
ThO Beam : Yale/Harvard	^{129}Xe Liquid : Princeton, Garching/Munich
YbF Beam : Imperial	^{223}Rn Trap : TRIUMF
PbF Trap : Oklahoma	^{213,225}Ra trapped : KVI, Argonne
HfF^{+} : JILA	Proton storage ring : BNL/COSY/FNAL?
GdIG Solid : Amherst,Yale,Indiana	Deuteron storage ring : Jülich ?

Why do we expect the electron, proton, neutron, ... EDMs $d \neq 0$?

- SM prediction is so small $\Rightarrow$ any observation $d_{n,p,e} \neq 0$ definitive evidence of new physics

Reasons to expect there is new physics leading to $d_{n,p,d,e}$ large enough to detect :

- Sakharov showed CP-violation required to generate matter-antimatter asymmetry in universe
  - CP-violation in SM $> 10^5$ too small to account for observations
  - Expect new sources of CP-violation
  - EDMs could be dramatically enhanced
- Most SM extensions predict many new particles and CP-violating phases
  - Predict dramatically enhanced EDMs : $|d_e| \approx 10^{-26} - 10^{-31}$ e·cm !
    $|d_{n,p,d}| \approx 10^{-25} - 10^{-31}$ e·cm !

$\Rightarrow$ Observed matter-antimatter asymmetry and theoretical prejudice suggest significant sources of T-violation beyond SM

$\Rightarrow$ $d_{n,p,d,e} \neq 0$ definitive evidence of new physics

$\Rightarrow$ Predicted $d_{n,p,d,e}$ within range accessible to new experiments

$\Rightarrow$ Good time to look for EDMs ! Must-do physics !

Effective Low Energy MSSM CP-violating Lagrangian

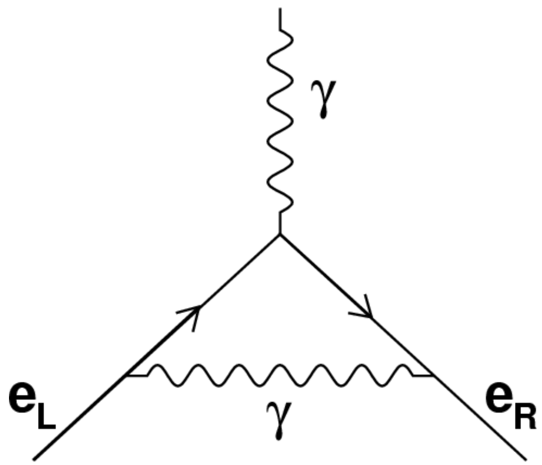
(From D. Demir *et al.*, Nucl. Phys. B **680**, 339 (2004))

$$\mathcal{L}_{\text{eff}} = \frac{g_s^2}{32\pi^2}\bar{\Theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3}wf^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G^{\mu,c}_{\beta} - \frac{i}{2}\sum_{i=e,u,d,s} d_i\bar{\Psi}_i\gamma_5\sigma^{\mu\nu}\Psi_i F_{\mu\nu} - \frac{i}{2}\sum_{i=e,u,d,s} d^c_i\bar{\Psi}_i g_s\gamma_5\sigma^{\mu\nu}\lambda^a\Psi_i G^a_{\mu\nu}$$

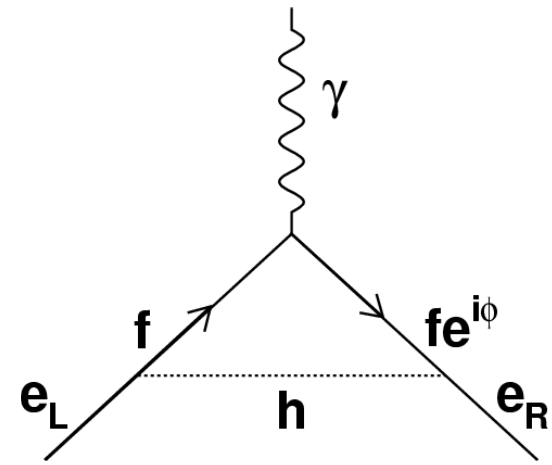
- Contributions : $\bar{\Theta}$, Weinberg 3-gluon, EDMs of e and quarks d_i, chromo-edms of quarks d_i^c
- $|d_n|$ limits $\rightarrow$ $\bar{\Theta} < 1 \times 10^{-10}$, *a priori* $\bar{\Theta} \approx 0 - 2\pi$
  - If Peccei-Quinn axions exist $\bar{\Theta} \rightarrow 0$
  - Radiative corrections to $\bar{\Theta}$ may induce non-negligible EDM
- The CP-odd term cubic in $G^a_{\mu\nu}$ seldom dominates the EDM of a nucleon
- For given manner of SUSY breaking $w,\ d_i,\ d_i^c$ can be calculated
  - From quark level to nucleon level involves nuclear models : $w,\ d_{u,d,s},\ d^c_{u,d,s} \Rightarrow d_n,\ d_p$
  - $d_n = -d_p \approx 3 \times 10^{-16}\,\bar{\theta}$ e·cm if CP-violation due to $\bar{\theta}_{\text{QCD}}$
  - $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u + 0.83e(d^c_u + d^c_d) - 0.27e(d^c_u - d^c_d)$
  - $d_p = \frac{4}{3}d_u - \frac{1}{3}d_d + 0.83e(d^c_u + d^c_d) + 0.27e(d^c_u - d^c_d)$
  - $d_n = \eta\,(\Delta_d d_d + \Delta_u d_u + \Delta_s d_s)$, ...
  - $d_p \approx d_n$ if dominated by heavy quarks, d_d from other combinations of terms

$\Rightarrow$ Need measurements in many systems $d_p,\ d_n,\ d_d$, ... to extract parameters of CP violation

  - d_e "easily" extracted from EDM, d_A, observed in atom or molecule



$\Longleftrightarrow$



⇒ Energy shift from anomalous mag. moment

$$\Delta E \approx (g-2)\ \mu_B\ |\mathbf{B}|/2$$
$$\approx \frac{\alpha}{2\pi}\ \frac{e\hbar}{2m_e c}\ |\mathbf{B}|$$

⇒ Energy shift from an electric dipole moment

$$\Delta E \approx d_e \cdot \mathbf{E}$$
$$\approx \frac{\alpha}{2\pi}\ \frac{e\hbar}{2m_e c}\ |\mathbf{E}| \times \left(\frac{f}{e}\right)^2 \sin(\phi) \left(\frac{m_e}{m_h}\right)^2$$

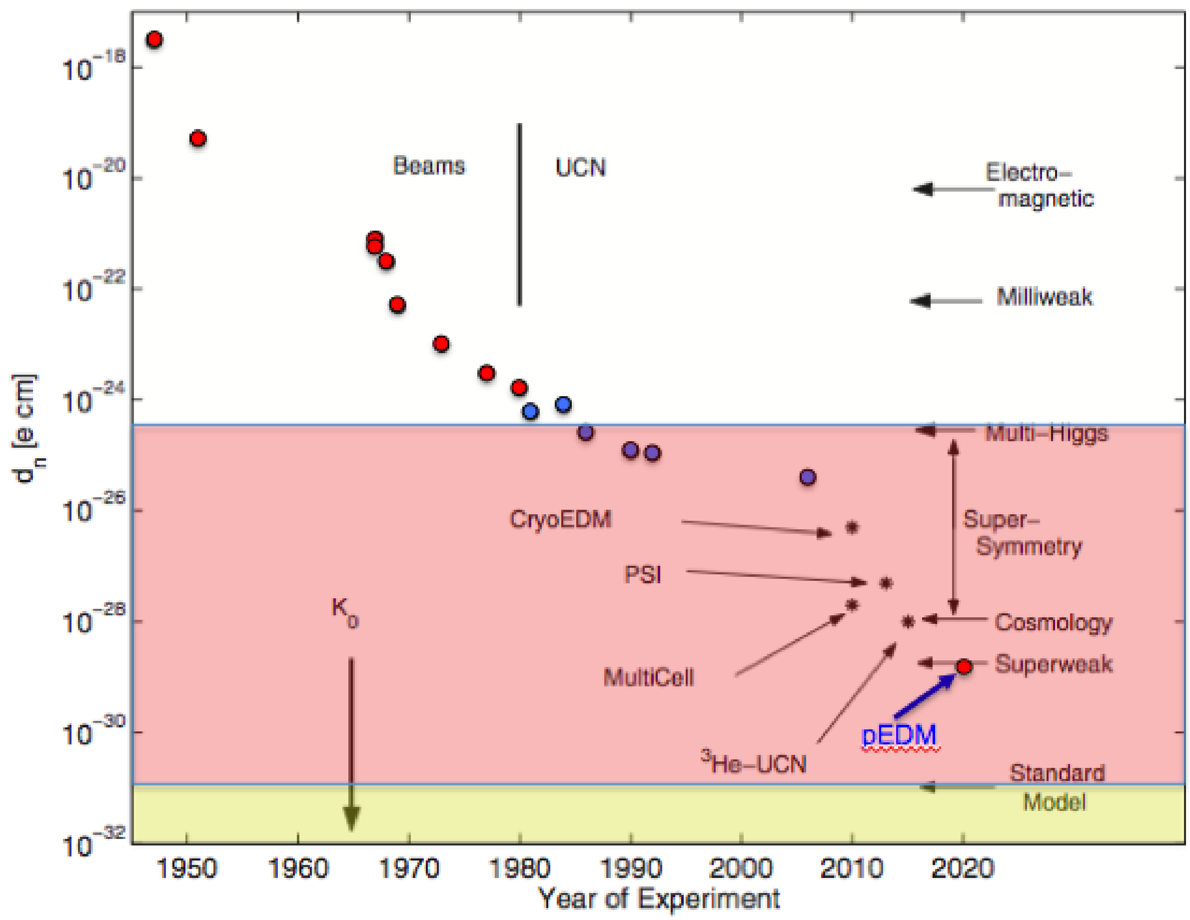
$$d_e \approx e\,\frac{\alpha}{4\pi}\ \sin(\phi)\ \frac{m_e}{m_h^2}, \quad \sin(\phi) \approx 1$$

$$\Rightarrow d_e \approx \frac{1}{137 \cdot 2\pi}\ \frac{1.05 \times 10^{-27}}{2 \cdot 9.1 \times 10^{-28} \cdot 3 \times 10^{10}} \left(0.5 \times 10^{-6}\right)^2 \left(\frac{1\ \mathrm{TeV}}{m_h}\right)^2\ e \cdot \mathrm{cm}$$
$$\approx 5\ \times\ 10^{-27} \left(\frac{1\ \mathrm{TeV}}{m_h}\right)^2\ e \cdot \mathrm{cm};\quad \text{for quarks } d_f \text{ almost 10 times larger}$$

⇒ Current limit $|d_e| < 1.0 \times 10^{-28}$ probes TeV mass scale, future experiments even more !

History and Future of Neutron EDM limits

J. Phys. G: Nucl. Part. Phys. **36** (2009) 104002 S K Lamoreaux and R Golub



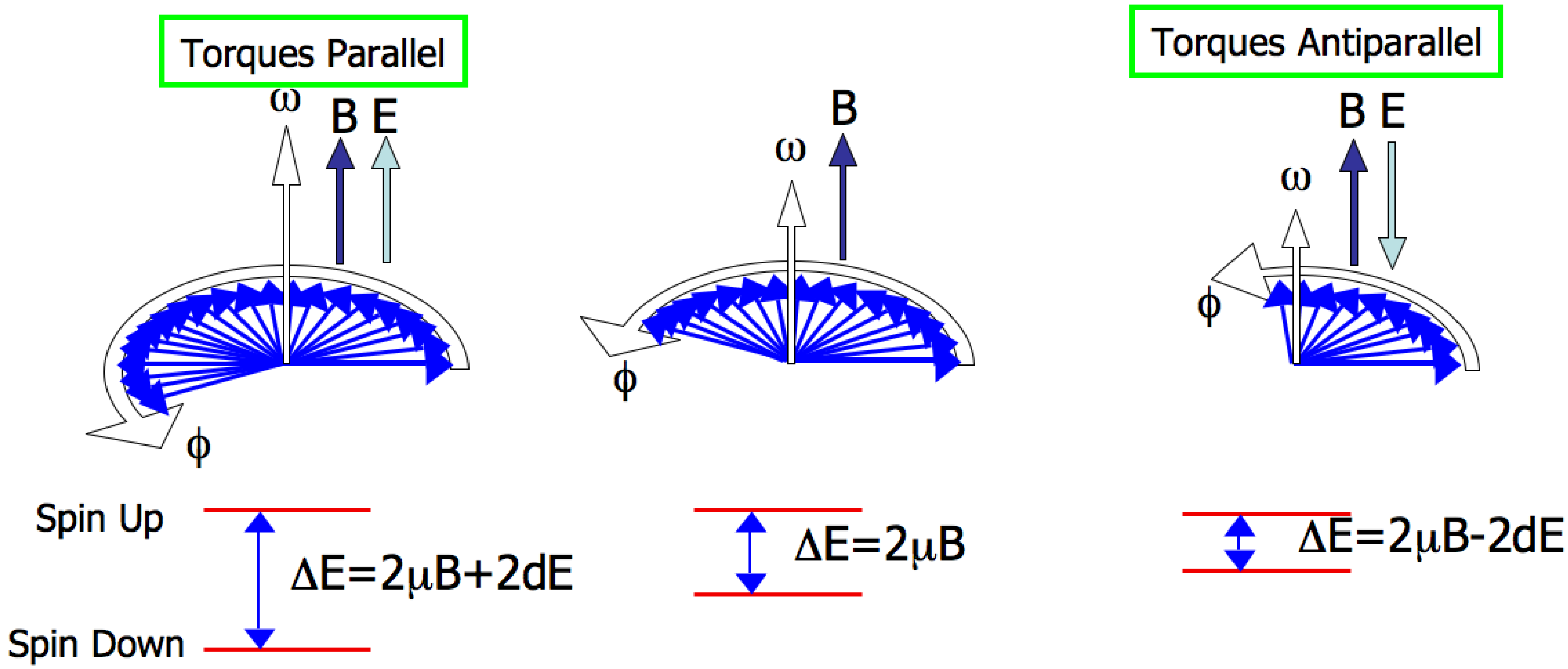
- Sensitive to much of SUSY parameter space, and scales of 100s of TeV, phases of $\lesssim 10^{-5}$ rad

$$d_f \approx e_f \frac{\alpha}{4\pi} \sin(\phi) \frac{m_f}{\Lambda^2} \quad f = \text{quark, lepton}$$

$$d_p \approx (10^{-22} - 10^{-24}) \times \left(\frac{1 \text{ TeV}}{M_{\text{SUSY}}}\right)^2 \sin\phi \quad e \cdot \text{cm (at 1 loop)}$$

Algorithm for finding an EDM

- Put system with unpaired spins in parallel E and B fields
- Spin polarize system perpendicular to fields (superposition of spin up and down)
- Torques from E and B fields lead to precession through angle ϕ in coherence time τ
- Flip E wrt B, look for change in ϕ ($i.e.$ look for energy shift).



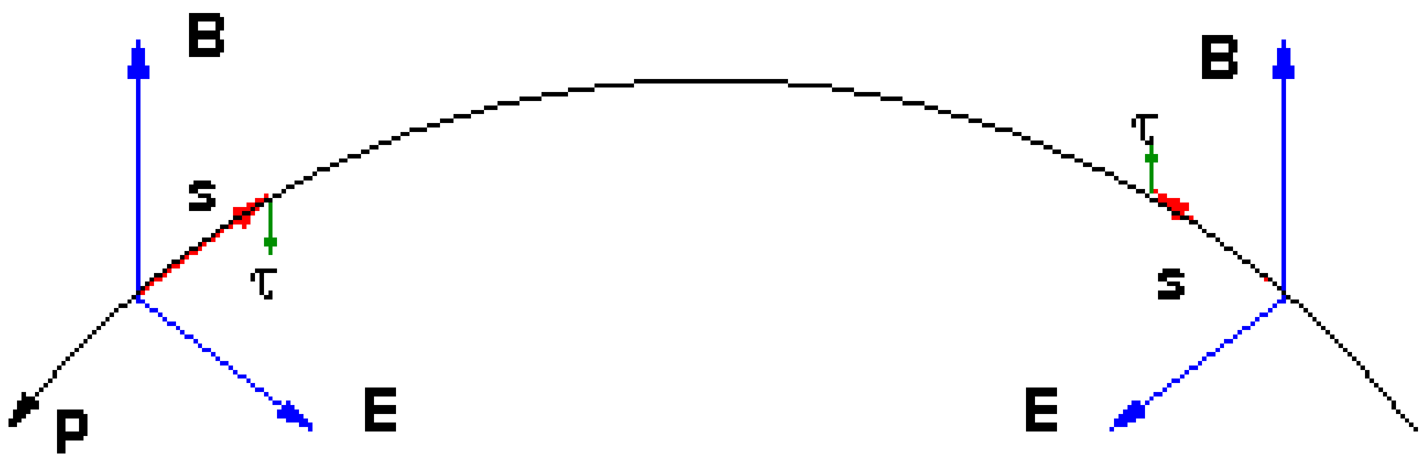
- Look for precession frequency shift $\Delta\nu = 4dE/h$
- For $E = 100$ kV/cm, $d_e = 1 \times 10^{-28}$ e·cm $\Rightarrow$ $\Delta\nu \approx 2$ nHz $\Leftrightarrow$ $B \approx$ few $\times 10^{-15}$ G
- Only works for neutral systems: neutron, atoms, molecules

Storage ring approach to measuring an EDM (Y. Semertzidis KAIST, Khriplovich)

- What about EDM searches in bare charged particles? Need a trap.
- Consider magnetic storage ring: in particle rest frame sees radial $\vec{E}$ and vertical $\vec{B}$ fields

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}_r + \vec{\mu} \times \vec{B}_v, \qquad \vec{\mu} = g\frac{e}{2mc}\vec{s}, \quad \vec{d} = \eta\frac{e}{2mc}\vec{s}$$

- 1st term, torque from EDM, precesses spin into vertical, out of plane: EDM signature
- 2nd term, torque from magnetic moment, precesses spin in plane



- If $g \neq 2$, torque from magnetic moment rotates spin vector in plane (anomalous precession)
- Torque from EDM $\vec{d} \times \vec{E}$ keeps changing sign; up, down, up, down, ...

⇒ Need to freeze this anomalous spin precession to see EDM

New approach to proton EDM : Magic Momentum Storage Ring

- Storage ring with vertical $\vec{E}$ fields only ($\vec{B}=0$, quantities in lab frame):

$$\vec{\omega}_s - \vec{\omega}_c = \vec{\omega}_a + \vec{\omega}_{EDM} = -\frac{e}{mc}\left[\frac{g-2}{2} - \left(\frac{mc}{p}\right)^2\right]\vec{\beta}\times\vec{E} + \eta\frac{e}{2mc}\vec{E}$$

- For proton, $a=(g-2)/2=1.79$: Eliminate ω_a at "magic" mom. $p=\frac{mc}{\sqrt{a}}=0.70$ GeV/c

⇒ Spin is frozen along mom., maximum sensitivity to EDM precessing spin out of plane :

$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{d}\times\boldsymbol{E} + \boldsymbol{\mu}\times\boldsymbol{B}_{\text{residual}}, \quad \text{where } |\boldsymbol{s}| = \hbar/2$$

$$\Rightarrow \omega_v = \frac{2\left(dE_{\text{radial}} + \mu B_{\text{radial}}\right)}{\hbar} \quad \text{is precession frequency of spin out of plane}$$

- The precession due to an EDM at the level of 10^{-29} e·cm given by :

$$\omega_v^{\text{EDM}} = \frac{2dE}{\hbar} = \frac{2dEc}{\hbar c} = \frac{2\times 1\times 10^{-31}\ \text{e}\cdot\text{m}\times 6.6\ \text{MV/m}\times 3\times 10^{8}\ \text{m/s}}{197\ \text{MeV}\cdot\text{fm}}$$

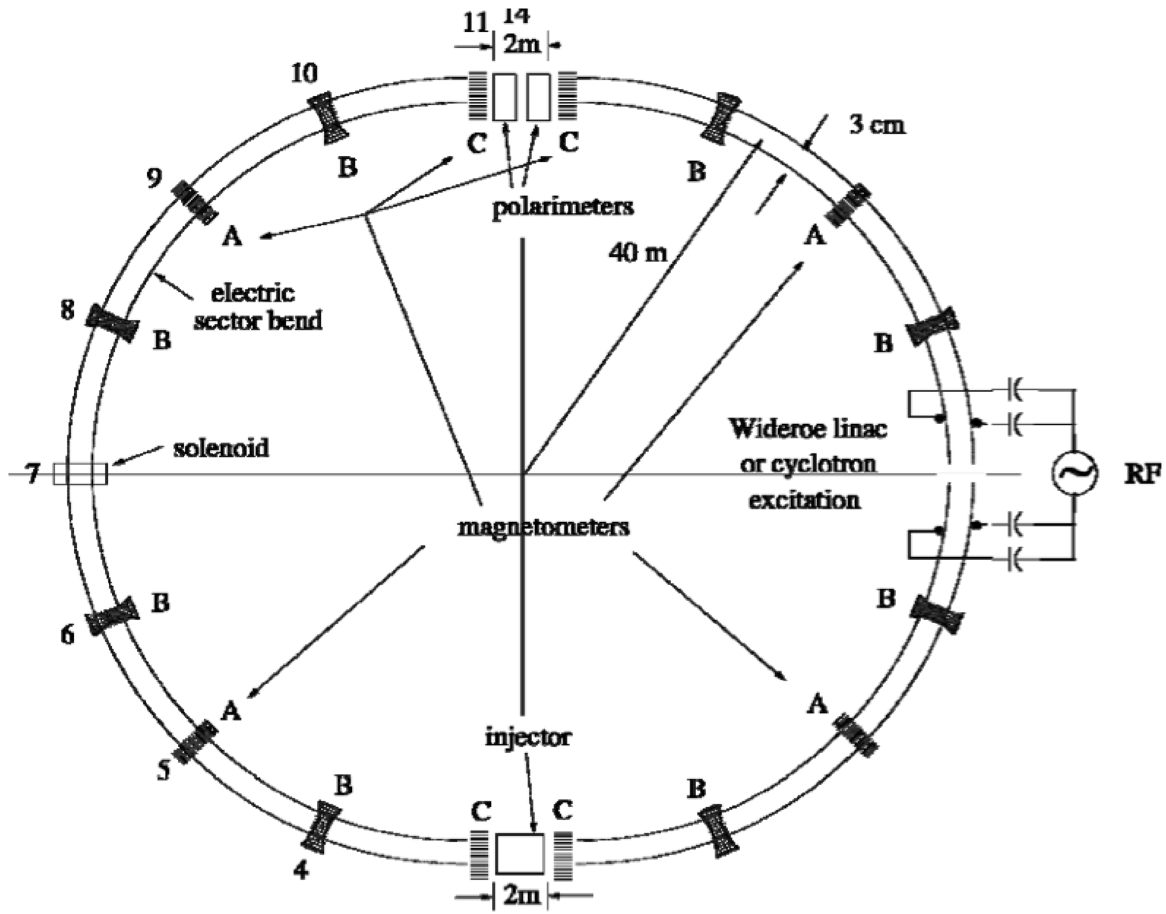
$$\omega_v^{\text{EDM}} = 2\ \text{nrad/s}, \quad \theta(t) = 2\,\frac{\text{nrad}}{s}\times\tau, \quad \tau \text{ is measurement time}$$

- That works out to 3.6° per year. Maximize θ by maximizing E and measurement time τ

⇒ Precession into vertical also caused by a radial magnetic field $\boldsymbol{B}_r$

- Effect on precession is indistinguishable from an EDM - is this fatal?

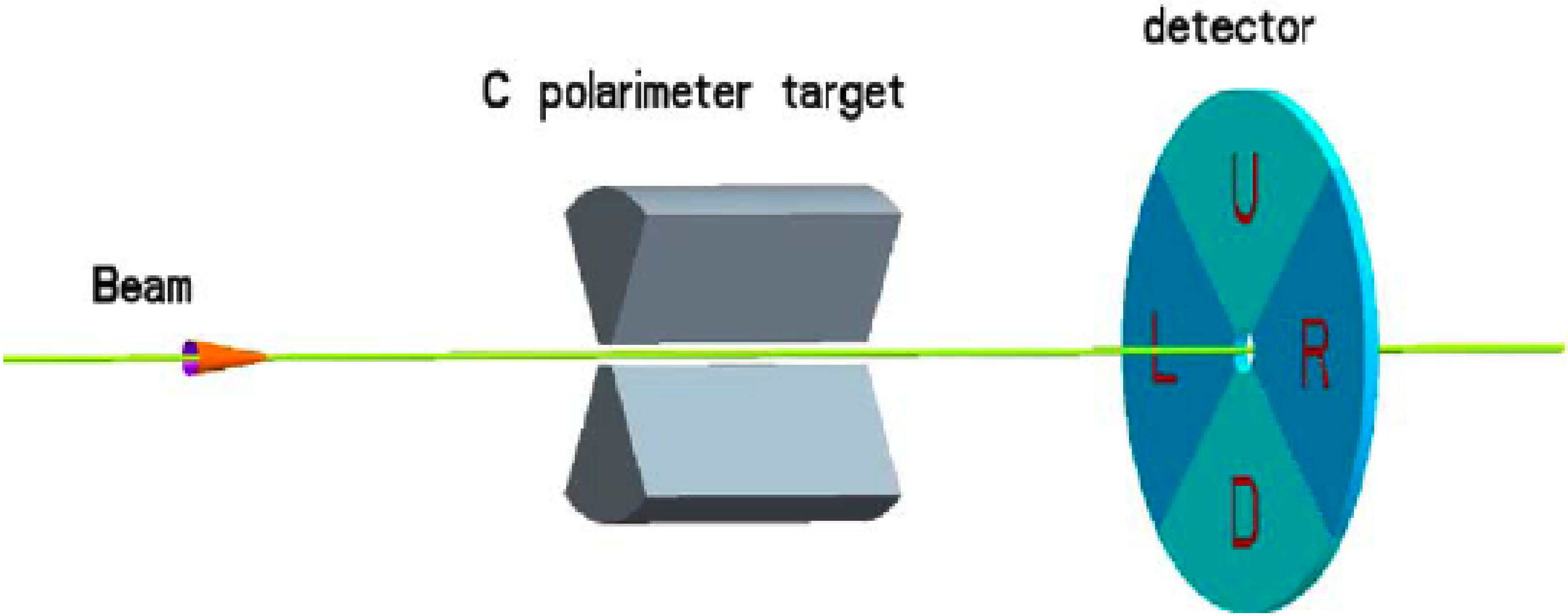
Proton EDM Measurement in a Storage Ring



- Purely electrostatic storage ring, 500 m circumference, 80% coverage with 6.6 MV/m cylindrical deflectors
- Straight sections for AG electrostatic quadrupoles, polarimeters, SQUIDs for BPMs/B_r measurement
- Inject 100 bunches of 7×10^8 polarized protons CW and CCW, simultaneously
- Use RF for bunching, RF to prepare bunches with positive/negative helicity
- Measure growth of vertical spin component with polarimeters over spin coherence time 1000 seconds
- Subtracting CW-CCW signal isolates EDM from most systematics

Challenges of a Proton EDM Measurement in a Storage Ring : Polarimetry

- Proton spin direction determined with polarimeter based on elastic pC scattering
- Vertical polarization yields difference in left-right scattering rates : P=(L-R)/(L+R)
- $d_p = 10^{-29}$ e cm corresponds to 3 ppm effect in ratio
- Polarimeter systematics : beam motion on target, beam position and angle, rate effects, gain changes



- See dedicated talk by Ed Stephenson on polarimetry Parallel-I S9
- Parallel IV S9 talks by Andreas Lehrach on storage ring EDMS, Des Barber on spin resonances, Artem Saleev on storage ring EDM systematics, Sebastian Mey on Spin Manipulators at COSY, Paulo Lenisa on Machine development for spin

Challenges of a Proton EDM Measurement in a Storage Ring : Polarimetry

- Analyzing power of polarimeter is very well matched to proton kinetic energy of 232 MeV
- Substantial work has been done with EDDA at COSY (Ed Stephenson, Indiana, COSY, KVI, Jülich)
- Only 1% of scattered p are within acceptance of detector, energy range etc
- Technique seems viable, systematics below 1 ppm appear possible

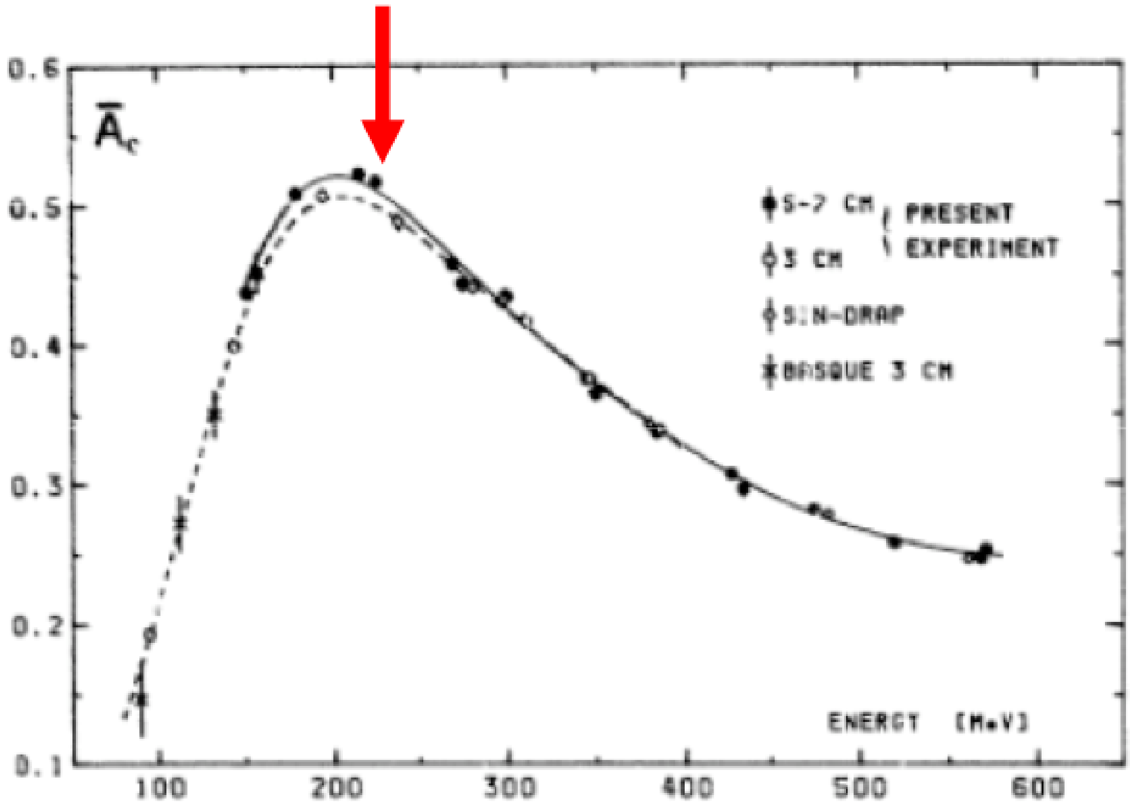


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

Limitation on the pEDM experiment due to radial magnetic fields

- Non-zero ambient $\boldsymbol{B}_r$ mimics EDM, and results in vertical Lorentz force
- Lorentz force in opposite directions for CW and CCW beams
- Compensated by net vertical electric field : $\boldsymbol{E}_v = -\boldsymbol{\beta} \times \boldsymbol{B}_r$
- Spin precession in vertical due to $\boldsymbol{B}_r$ using lab-frame quantities (see Jackson) :

$$\begin{aligned}
\frac{d\boldsymbol{s}}{dt} &= \frac{e}{mc}\boldsymbol{s}\times\left[\left(\frac{g}{2} - 1 + \frac{1}{\gamma}\right)\boldsymbol{B}_r - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\boldsymbol{\beta}\times\boldsymbol{E_v}\right] \\
&= g\frac{e}{2mc}\frac{1}{\gamma^2}\boldsymbol{s}\times\boldsymbol{B}_r \\
&= \frac{1}{\gamma^2}\boldsymbol{\mu}\times\boldsymbol{B}_r \quad \text{(normal relation modified by E field)}
\end{aligned}$$

⇒ What magnitude of $\boldsymbol{B}_r$ is equivalent to EDM precession into the vertical ω_v?

$$\begin{aligned}
\hbar\omega_v &= 2\mu B_r/\gamma^2 \Rightarrow \\
B_r &= \frac{\hbar\omega_v}{2\mu}\gamma^2 = \frac{1.05\times 10^{-34}\ \mathrm{J\cdot s}\times 3\times 10^{-9}\ \mathrm{rad/s}\times 1.25^2}{2\times 1.41\times 10^{-26}\ \mathrm{J/T}} = 2.2\times 10^{-17}\ \mathrm{T}
\end{aligned}$$

⇒ Net radial magnetic field of 0.22 pG (0.022 fT!) would causes precession equivalent to pEDM of $d_p = 10^{-29}\ e\cdot$cm

⇒ Radial $\boldsymbol{B}$ field splits CW and CCW beam in vertical direction

- Lorentz force from B_r of opposite sign for CW and CCW beams ⇒ they split vertically
- Expanding $\boldsymbol{B}_r$ in multipoles, write the equation of motion in vertical y :

$$\frac{d^2y}{d\theta^2} + Q_y^2 y = \frac{\beta c R_0}{E_r} \sum_{N=0}^{\infty} B_{rN} \cos\left(N\theta + \phi_N\right)$$

- This has solutions :

$$\delta y(\theta) = \pm \sum_{N=0}^{\infty} \frac{\beta c R_0 B_{rN}}{E_r} \left[\frac{1}{Q_y^2 - N^2}\right] \cos(N\theta + \phi_N) + y_0 \cos(Q_y\theta + \phi_Q),$$

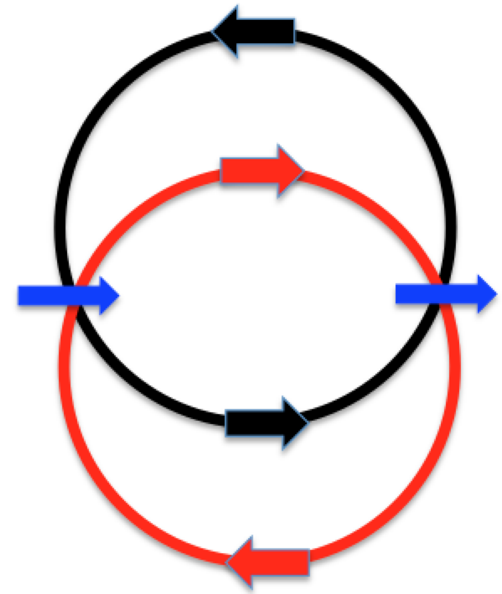
- Q_y is vertical betatron tune, last term is vertical betatron oscillation
- Distortion of equilibrium orbit of opposite sign for the CW and CCW beams
- Only N=0 term, B_{r0}, leads to $\langle \delta y_{CW} - \delta y_{CCW} \rangle \neq 0$
- With vertical tune $Q_y \approx 0.1$, average vertical displacement of each beam :

$$\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm \frac{0.6 \times 3 \times 10^8 \text{ m/s} \times 40 \text{ m} \times 2.2 \times 10^{-17} \text{ T}}{10.5 \times 10^6 \text{ V/m} \times 0.1^2} = \pm 1.5 \times 10^{-12} \text{ m}.$$

⇒ Net radial magnetic field B_r of 2.2×10^{-17} T splits the CW and CCW beams vertically by ≈ 3.0 pm)

Separated counter-circulating beams produce a magnetic dipole

- To detect splitting, consider $\boldsymbol{B}$ fields created by beams
- For displacements from origin by δx and δy, $\boldsymbol{B}$ from single beam :



$$\boldsymbol{B}(r,\phi) = \frac{\mu_0}{4\pi}\frac{2I}{r}\left\{\left[-\sin\phi + \left(-\frac{\delta x}{r}\sin 2\phi + \frac{\delta y}{r}\cos 2\phi\right)\right]\hat{\boldsymbol{x}} + \left[+\cos\phi + \left(-\frac{\delta x}{r}\cos 2\phi + \frac{\delta y}{r}\sin 2\phi\right)\right]\hat{\boldsymbol{y}}\right\}$$

- If CW & CCW beams split by $\pm\delta y$, can detect at $\phi = \{0,\pi\}$ looking at $\boldsymbol{B}\cdot\hat{\boldsymbol{x}}$

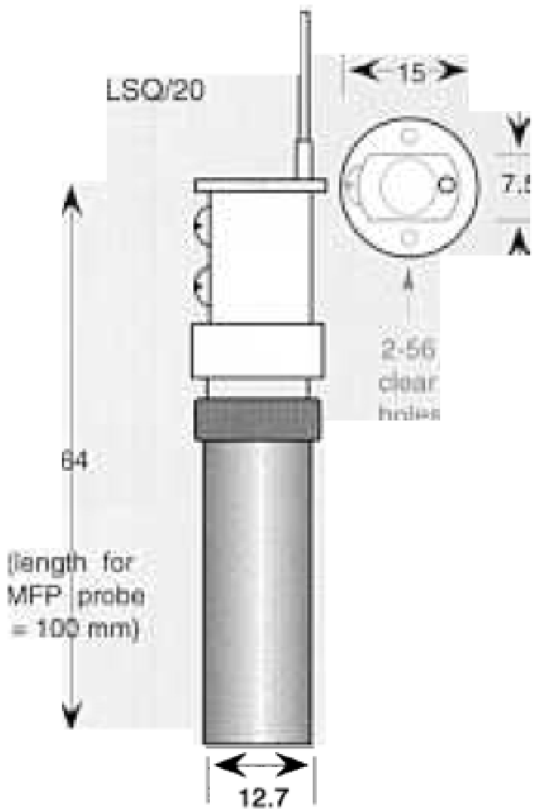
$\Rightarrow$ To move signal off of DC, modulate the vertical tune at ω_m between 20 Hz and 1 kHz

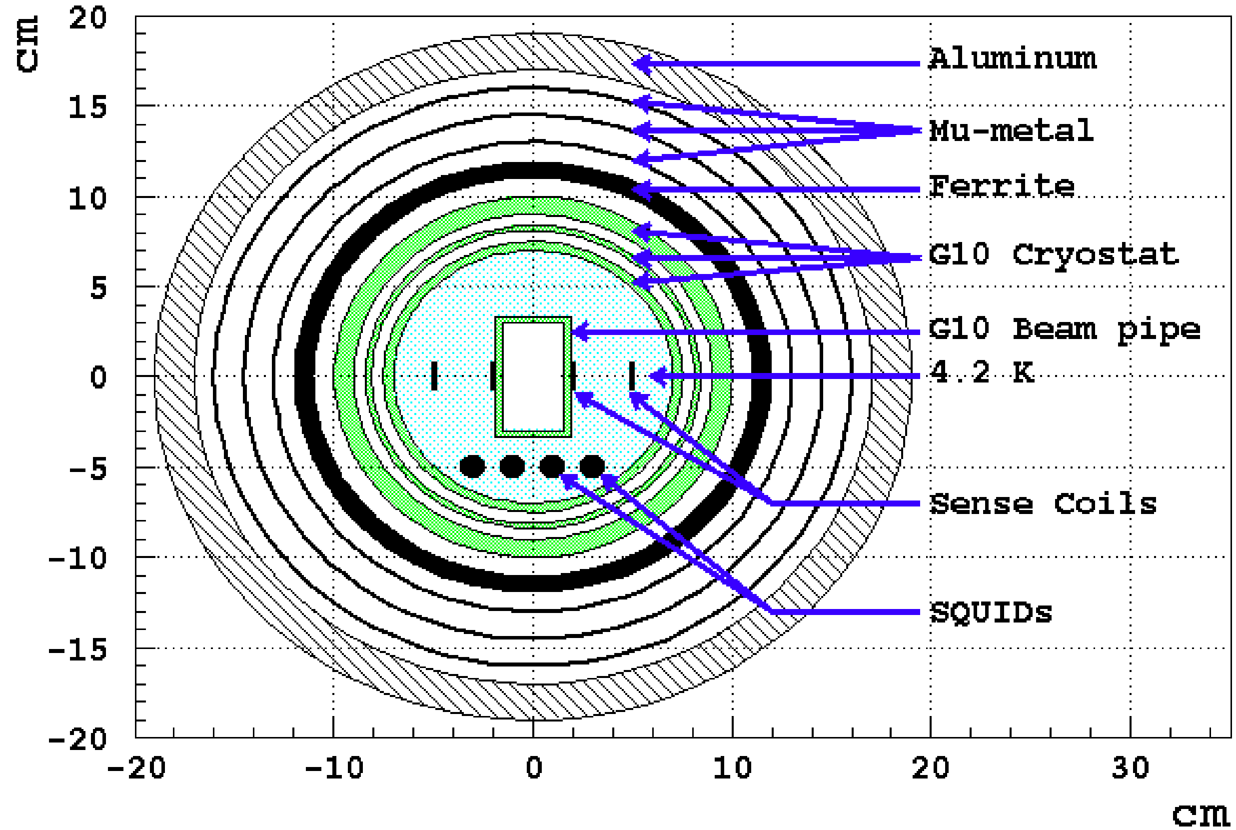
- Set $Q_y \Rightarrow Q_y \times (1 - m\cos(\omega_m t))$ where modulation depth $m \approx 0.1$

$$\Rightarrow \boldsymbol{B}(r,\phi=(0,\pi),\omega_m) = \frac{\mu_0}{4\pi}\frac{2I}{r}\left[\frac{\delta y \times 4m\cos\omega_m t}{r}\right]\hat{\boldsymbol{x}}.$$

- Modulating 3 pm splitting of beams by 20% yields peak field of 0.6×10^{-3} fT at ω_m

Schematic of a SQUID BPM system





- Tristan Technology LSQ/20 SQUID
- 64 mm long, 12.7 mm diameter
- ≤ 1 fT/$\sqrt{\mathrm{Hz}}$

- Beam's eye view schematic of a SQUID BPM system
- Sense coils, leads, SQUIDs at 4.2K; leads and SQUIDs in superconducting shields, Ferrite and μ-metal at room temp.
- For $\omega_m > 150$ Hz, shield noise $\delta B < 1$ fT/$\sqrt{\mathrm{Hz}}$
- Use lock-in amplifier at ω_m to extract signal, provide feedback
- Will use about 100 SQUIDs in 6 sections to meet the spec with S/N>5

Ring and Beam parameters for a Proton EDM Experiment

Length of E-field Deflectors	400 m
Bending Radius, R_0	64 m
Plate Spacing, d	3 cm
Plate Height	20 cm
Deflector Shape	Cylindrical
Radial E-Field, E_0	6.6 MV/m
Number of Straight Sections	47
Straight Section Lengths	2 m (quads), 3 m (polar., SQUID BPMs)
Total Circumference	500 m
Number of Bunches	100
Protons per Bunch	7×10^8
RMS Momentum Spread $(dp/p)_{\rm rms}$	2.9×10^{-4}
Horizontal Beta Function, $\beta_{x,\ max}$	29.1 m
Vertical Beta Function, $\beta_{y,\ max}$	204 m
Horizontal Tune, Q_x	2.32
Vertical Tune, Q_y	0.31
Vertical Emittance (RMS, Normalized)	2.2 mm·mrad
Horizontal Emittance (RMS, Normalized)	0.3 mm·mrad

Effect	Remediation
Radial B-Field	SQUID BPMs, magnetic shielding to below 0.1-1 nT everywhere
Geometrical Phase	Plate alignment better than 100 μm, CW and CCW storage, polarimeter placement around ring, magnetic shielding, BPM to 100 μm eliminates effect
Non-radial E-field	CW and CCW beams cancel the effect
Vert. Quad Misalignment	BPMs sensitive to vertical beam oscillations common to CW and CCW beams
Polarimetry	Use positive and negative helicity protons in both CW and CCW beams
Image Charges	Use vertical metallic plates except in quads, Quad plate aspect ratio reduces effect
RF Cavity Misalignment	Limit longitudinal impedance to 10 kΩ CW and CCW beams cancel the effect

⇒ Do not need to reduce B_r to fT level, just measure with sub-fT resolution

- Can reduce B_r wth feedback if necessary

⇒ Plot ds_v/dt versus B_r. Since $ds_v/dt = d \times E + \mu \times B_r$, non-zero intercept is EDM

$$\delta d_p \approx \frac{2\hbar}{eE_R AP\sqrt{N_c f T_{\rm tot}\tau_{\rm coh}}}$$

E_R : 6.6 MV/m radial electric field over 80% of ring
A : 0.6 analyzing power of polarimeter
P : 0.8 proton beam polarization
N_C : 1.4×10^{11} protons stored per cycle
f : 0.0055 useful fraction of events
$T_{\rm tot}$: 10^4 number of fills of storage ring
$\tau_{\rm coh}$: 10^3 seconds spin coherence time

$\delta d_p \approx 1.9 \times 10^{-29}$ e·cm / year

Compares favorably with current limit $|d_n| \leq 10^{-26}$ e·cm
Comparable with goal at SNS of $\delta d_n \approx 10^{-28}$ e·cm

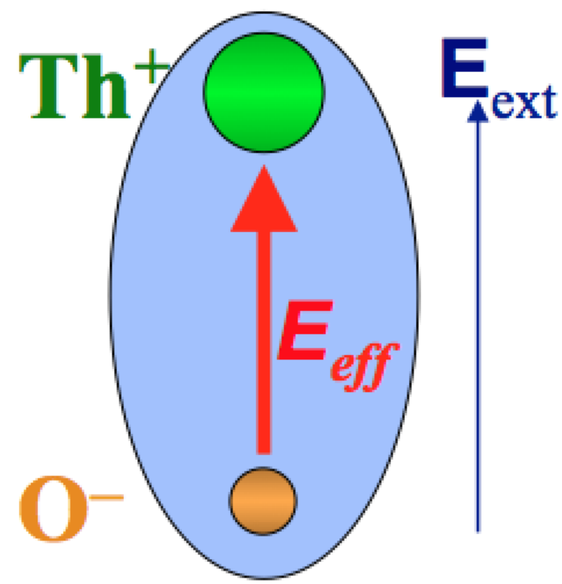
eEDM: Amplifying the Electric Field with a Paramagnetic Polar Molecule

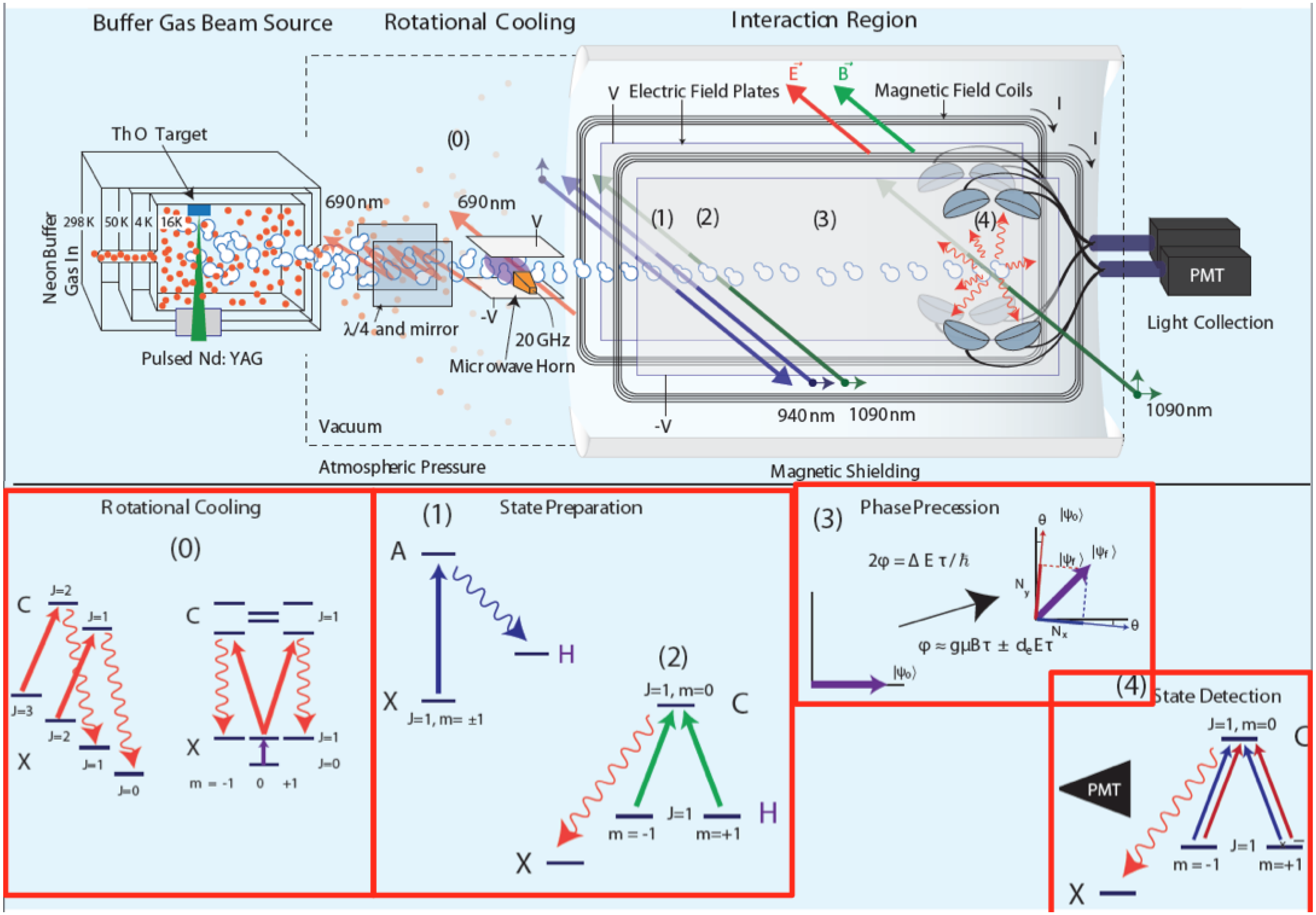
- Try to detect d_e in neutral atom or molecule in $\vec{E}_{\text{ext}}$
- Naively, net $\vec{E}$ on e^- in atom is zero $\Rightarrow$ no linear Stark shift observable
- Sandars discovery: relativistic effects yield $\Delta E \equiv \vec{d}_a \cdot \vec{E}_{\text{ext}} \equiv R d_e E_{ext}, \quad R \gg 1, \quad d_a \gg d_e$
- Energy shift due to electron EDM in atom can be larger than EDM shift of bare e^- in same field (R is -585 in thallium, 100 kV/cm $\Rightarrow$ -58 MV/cm)
- In polar molecules, large internal fields : can be fully polarized along external fields of order 10 V/cm
- Valence electron feel fields $E_{\text{eff}} \approx \alpha^2 Z^3 e/a_0^2 \approx 100$ GV/cm (ThO*)
- Bohn & Meyer : internal field of PbO a(1) state ≈ 25 GV/cm, ThO H state 104 GV/cm, WC 54 GV/cm

- Use heavy polar molecules with unpaired electron spin,
- Polarize $\vec{E}_{\text{int}}$ along $\vec{E}_{\text{ext}}$
- Polarize unpaired e^- parallel/anti-parallel to $\vec{E}_{\text{int}}$
- Look for $\Delta E = d_e E_{\text{int}}$:
  $d_e = 1 \times 10^{-29}$ e·cm $\Leftrightarrow$ 120 μHz
  $d_e = 1 \times 10^{-31}$ e·cm $\Leftrightarrow$ 1.2 μHz
- Motivates searches in PbO, YbF, HfF$^+$, ThO, WC

$\Rightarrow$ YbF had best limit $|d_e| < 1.0 \times 10^{-27}$ e·cm
J.J. Hudson *et al.*, Nature **473**, 493 (2011).

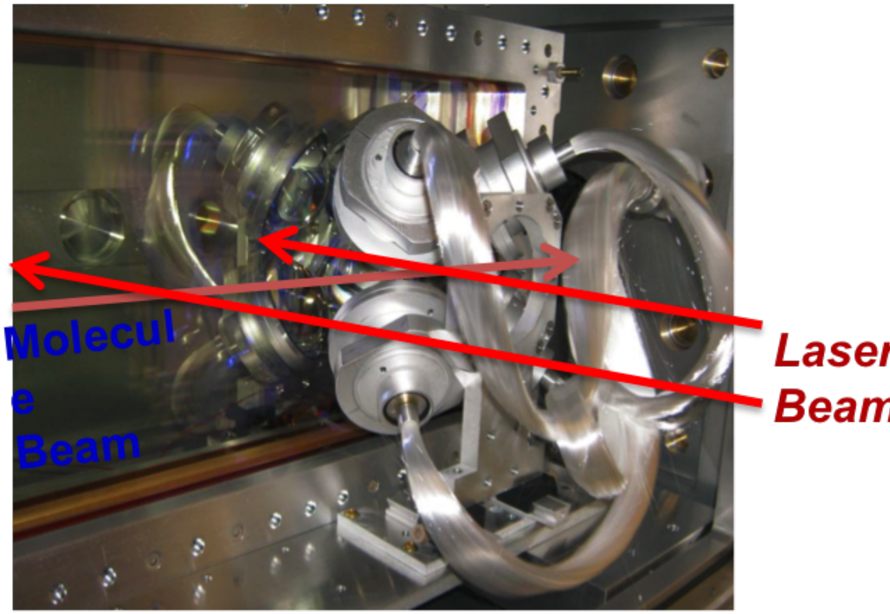
$\Rightarrow$ 2014: ACME Collab: ThO*, $|d_e| < 8.7 \times 10^{-29}$ e·cm



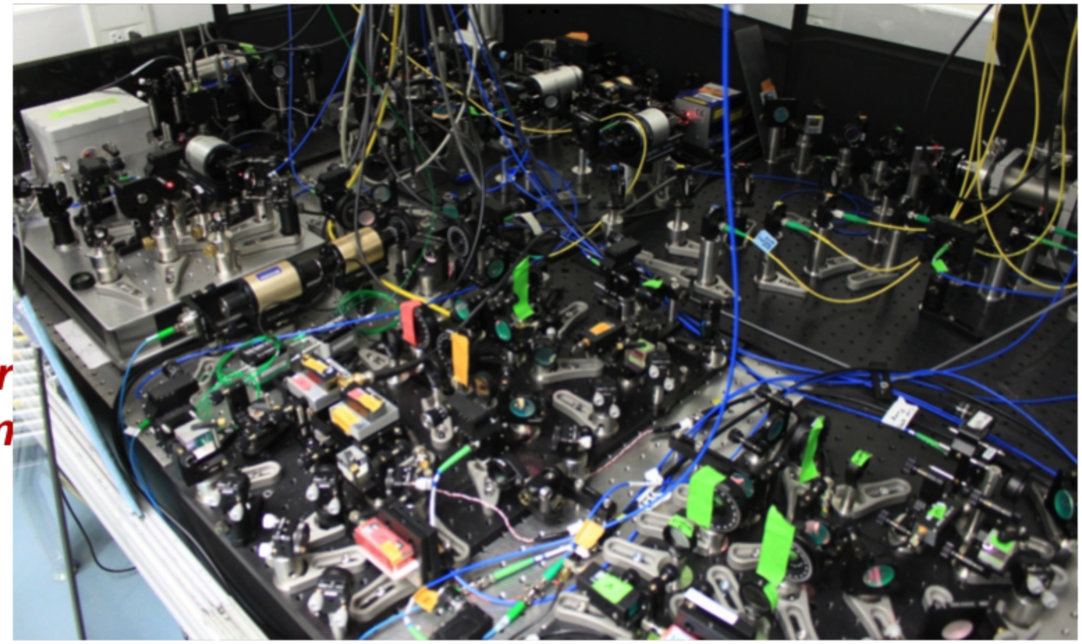


- New limit on electron EDM: $|d_e| < 8.7 \times 10^{-29}$ e·cm. More than factor 10 improvement
- J. Baron *et al.* (ACME Collaboration), "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron", Science **343** (6168), 269 (2014)

Transparent E-Field Plates and Light Collection



Several optical tables, 10+ lasers, dozens of modulators,



- Very detailed investigation and control of systematics
- Many improvements: electrostatic focusing of beam, stimulated vs. spontaneous emission state prep., thermochemical beam source, improved fluorescence detection, cycling fluoresence, longer integration time
- Factor of 300 or more gain in $\sqrt{N}$ appears possible !!!
- Other molecular eEDMs experiments: Ed Hinds YbF, and E. Cornell & Jun Ye HfF^+
- Pictures from D. DeMille

- Current limit $|d_\mu| < 1.8 \times 10^{-19} e$·cm (95%C.L.)
  (G.W. Bennett *et al.* (Muon g-2 Collaboration), Phys. Rev. D **80**, 052008 (2009))
- "Naive" Scaling:

$$d_\mu^{\rm NP} \propto \frac{m_\mu}{m_{\rm NP}^2} \Rightarrow d_\mu \approx \frac{m_\mu}{m_e} d_e < 1.8 \times 10^{-26}\ e \cdot {\rm cm}$$

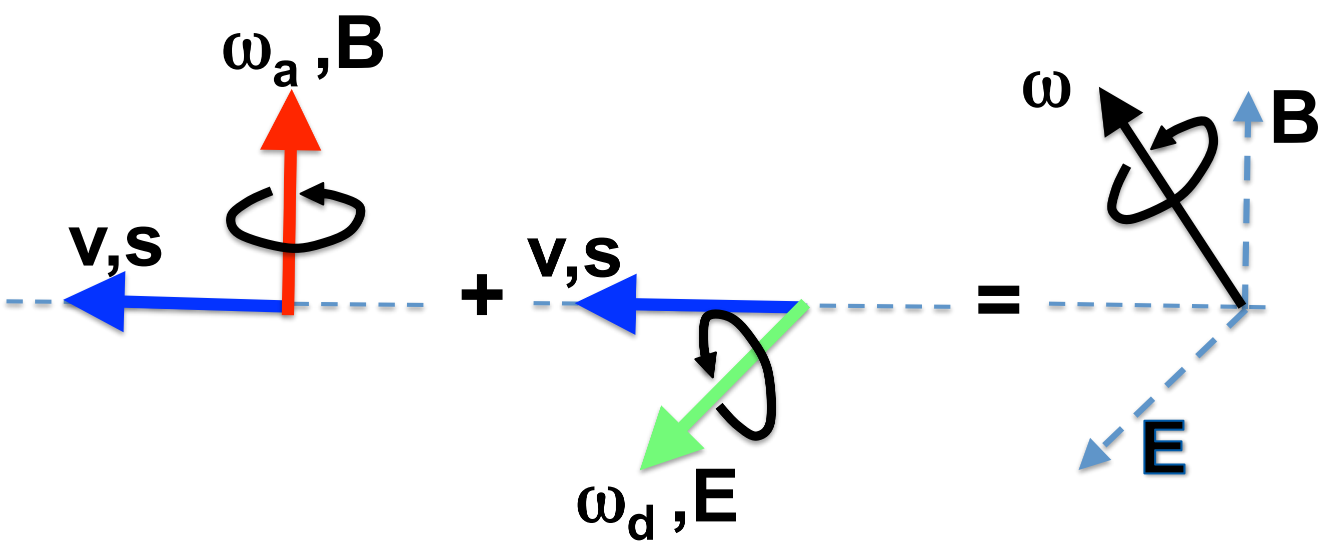
- Models exist with other mass scalings:
  - K.S. Babu, S.M. Barr, and I. Dorsner, "Scaling of lepton dipole moments with mass", Phys. Rev. D **64**, 053009 (2001),
  - J. Feng, K. Matchev, and Y. Shadmi, "Theoretical expectations for the muon's electric dipole moment", Nucl. Phys. B **613**, 366 (2001);
  - K.S. Babu, B. Dutta, and R. Mohapatra, "Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing", Phys. Rev. Lett. **85**, 5064 (2000).
- In supersymmetry: nondegenerate scalar mass matrices, slepton flavor violation
- Can be enhanced by several effects simultaneously: $d_\mu \approx 10^{-22}\ e$·cm
- Typically such large d_μ coupled with lepton-flavor violating effects

⇒ Significantly improved bounds on muon EDM could be sensitive to surprises

⇒ Important to search for EDMs in 2nd (and 3rd) generation of particles

- Store polarized muons using vertical $\vec{\boldsymbol{B}}$
- Precession of spin with respect to momentum given by :

$$\vec{\boldsymbol{\omega}} = \underbrace{\frac{e}{m}\left[a\vec{\boldsymbol{B}} + \left(-a + \frac{1}{\beta^2\gamma^2}\right)\vec{\beta}\times\vec{\boldsymbol{E}}/c\right]}_{\vec{\omega}_a\text{ : magnetic moment anomaly, } a\equiv(g-2)/2} + \underbrace{\frac{d}{2\hbar}\left[\vec{\boldsymbol{E}} + \vec{\beta}c\times\vec{\boldsymbol{B}}\right]}_{\vec{\omega}_d\text{ : EDM}}$$

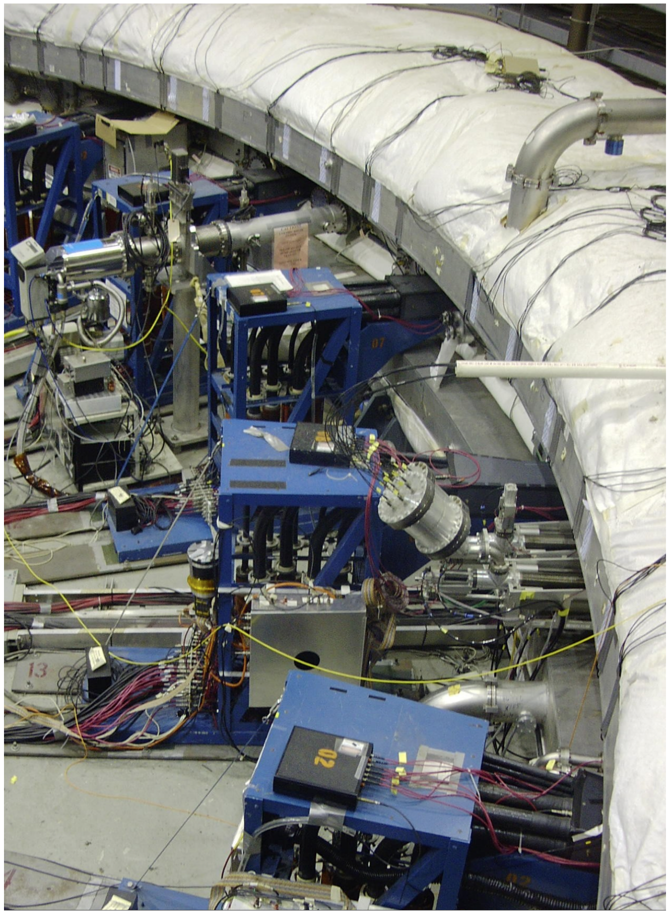


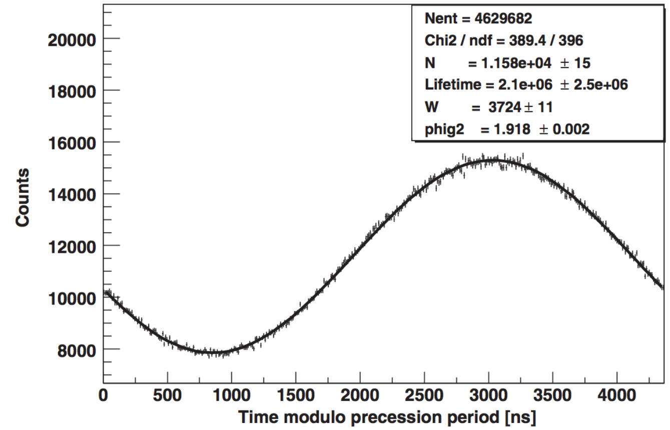
$\Rightarrow$ $\omega_{\text{obs}} = \sqrt{\omega_a^2 + \omega_{\text{EDM}}^2}$, $d_\mu < 3.9 \times 10^{-19}$ $e\cdot$cm

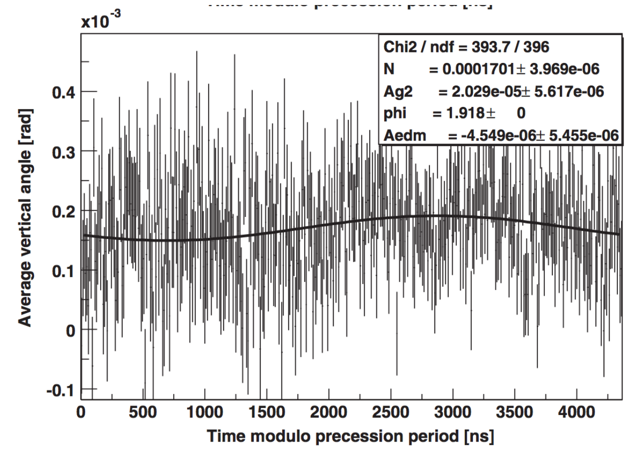
$\Rightarrow$ EDM spin precession into vertical is reversed by $g-2$ precession

$\Rightarrow$ Letters of intent for frozen spin methods for muon EDM have been developed

Muon EDM search in the BNL E821 and Fermilab E989 Muon g-2 Storage Rings







- EDM signature: oscillation of vertical angle/position of decay positrons on detector at g-2 frequency, 90° out of phase
- Main BNL E821 systematic: alignment of detectors coupled with breathing of vertical width of beam
- FNAL E989 new tracking detectors: improved alignment, acceptance: reduce precession plane tilt uncertainty from 4.4 μrad in E821 to 0.4 μrad
- FNAL E989 should improves limit by factor 100: $|d_\mu| < 1.8 \times 10^{-21}$ e·cm

Summary and Outlook

- Non-zero EDM would be a clear indicator of new physics
- Many reasons to expect EDMs of magnitude within reach of current and new experiments
- Important to measure EDMs in many species to interpret origin
- Significant progress in electron EDM limits likely in next few years
- Significant improvement in muon EDM (factor 100) possible in next 5 years

$\Rightarrow$ Important to undertake R&D and launch new proton EDM effort

Backup

Challenges of a Proton EDM Measurement in a Storage Ring : Spin Coherence

$$\vec{\omega}_a = -\frac{e}{mc}\left[a - \left(\frac{mc}{p}\right)^2\right]\vec{\beta}\times\vec{E}$$

$$d\omega_a = 2\frac{e}{mc}\left(\frac{mc}{p}\right)^2 \beta E \times \frac{dp}{p}$$

$$= \frac{dp}{p} \times 10^7 \text{ rad/s}$$

- If $dp/p \approx 2.5 \times 10^{-4}$, spin coherence time less than a millisecond!
- Will use RF cavity to cancel this first order effect, keep spins frozen

$$\text{At second order} \ : \ d^2\omega_a = \left(\frac{dp}{p}\right)^2 \frac{3}{2} \times 10^7 \text{rad/s} \approx 1 \text{ rad/s}$$

- Electrode design, length of straight sections, sextupoles adjusted so $d^2T_{\rm rev}/d\gamma^2 = 0$
- Sextupole with radial E field $\propto \ x^2 - y^2$, help correct 2nd order effect from $(dp/p)^2$

⇒ Spin coherence time : Use RF and sextupoles to reduce $d\omega_a/dp$ and $d^2\omega_a/dp^2$

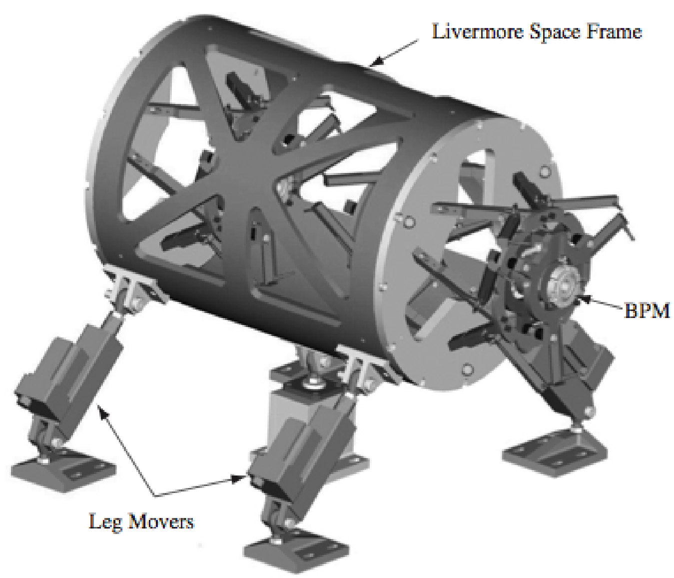
- Novosibirsk has achieved 10^7 turns, need $10^3 \ s \Leftrightarrow 10^9$ turns
- Have demonstrated SCT > 30 s at COSY with deuterons (electron-cooled) in Jan 2011
- Challenging, but appears possible

Magnetic field sensitivity required to measure beam splitting

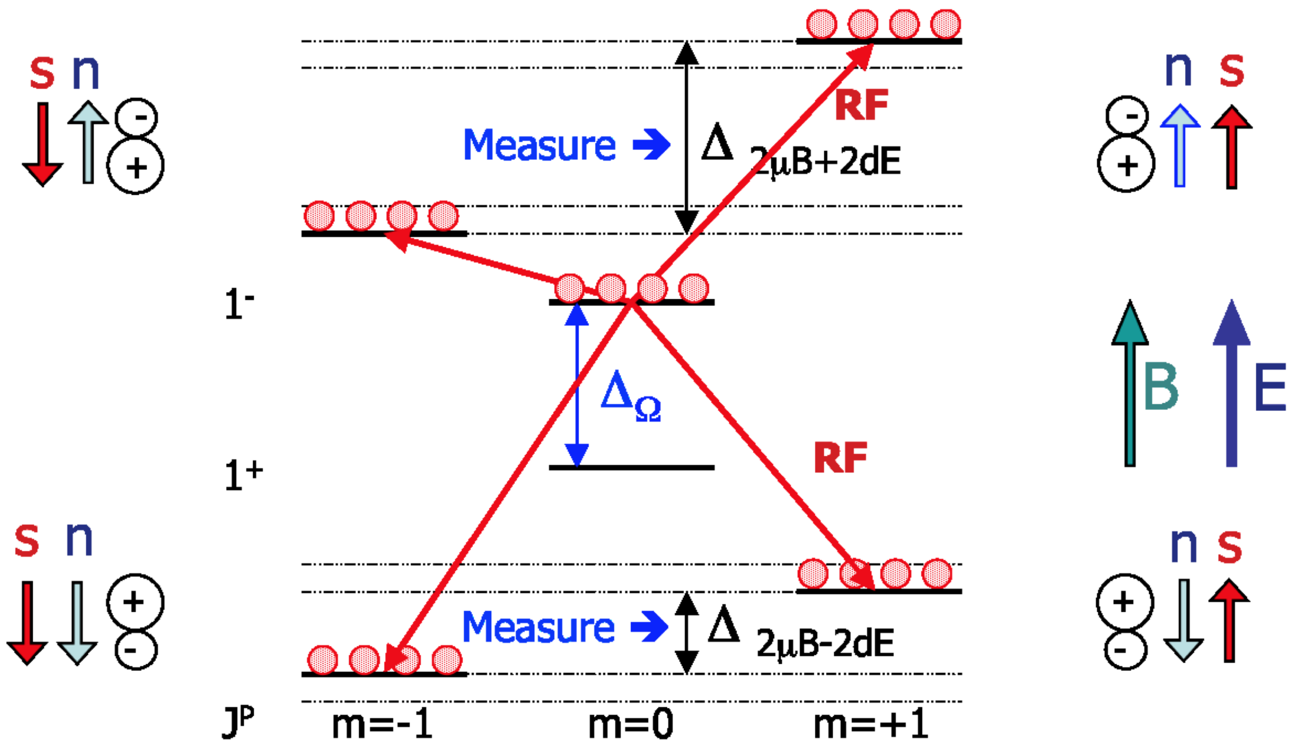
- Modulating 3 pm splitting of beams yields peak field of 0.6×10^{-3} fT at ω_m
- Have roughly 10^4 stores of 10^3 seconds to measure this field (for run duration 10^7 s)
- Need to determine $\boldsymbol{B}$ from beams to 0.6×10^{-1} fT per store of 1000 s
- Need sensitivity of $\approx\ 1.9$ fT$/\sqrt{\mathrm{Hz}}$ at ω_m for $S/N\ \approx\ 1$

$\Rightarrow$ Is equivalent to determining splitting of beams $2 \times \delta y \leq 0.3$ nm per store

- ILC final focus requires BPMs with nm level resolution for single shots of 10^{10} electrons
- Single shot resolution of 16 nm has been demonstrated with TM_{110} dipole-mode RF cavity BPMs (S. Walston *et al.*, Nucl. Instrum. Methods A **578**, 1 (2007))
- We just need to measure *relative* splittings of beams
- Position and tilt of our BPMs not nearly as critical as ILC application



Electron EDM search in Hund's case (c) Polar Molecule



- Prepare superposition : $|\psi_N(t=0)\rangle = \frac{1}{\sqrt{2}}[|M=1,N\rangle + |M=-1,N\rangle]$
- $M = \pm 1$ levels have different energies in B, E fields, acquire relative phase shifts
- $\phi_E \approx d_e \mathcal{E}_{\text{eff}} N t,\ \phi_B \approx g_J \mu_B B t$
- After time τ, components acquire relative phase shifts :
  $|\psi_N(t=\tau)\rangle = \frac{1}{\sqrt{2}}\left[e^{i\phi}|M=1,N\rangle + e^{-i\phi}|M=-1,N\rangle\right]$
- Detect projection of spin on $\hat{x}$ and $\hat{y}$ axes, look for E-field dependent shift