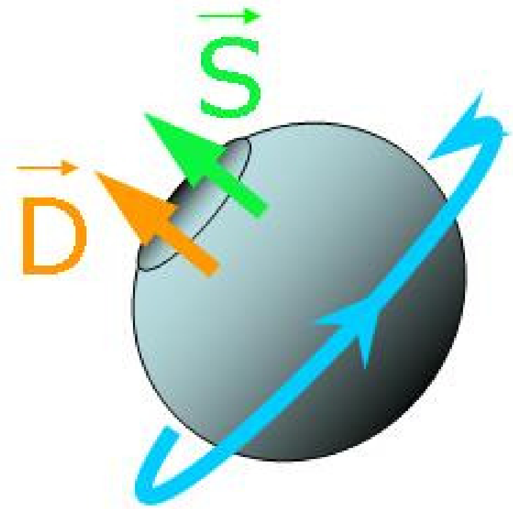
EDM Measurements : Testing Fundamental Symmetries with Nuclei, Atoms, and Molecules

Dave Kawall - UMass and RIKEN BNL Research Center



Precision ElectroWeak Interactions, College of William and Mary, Aug.17 2005

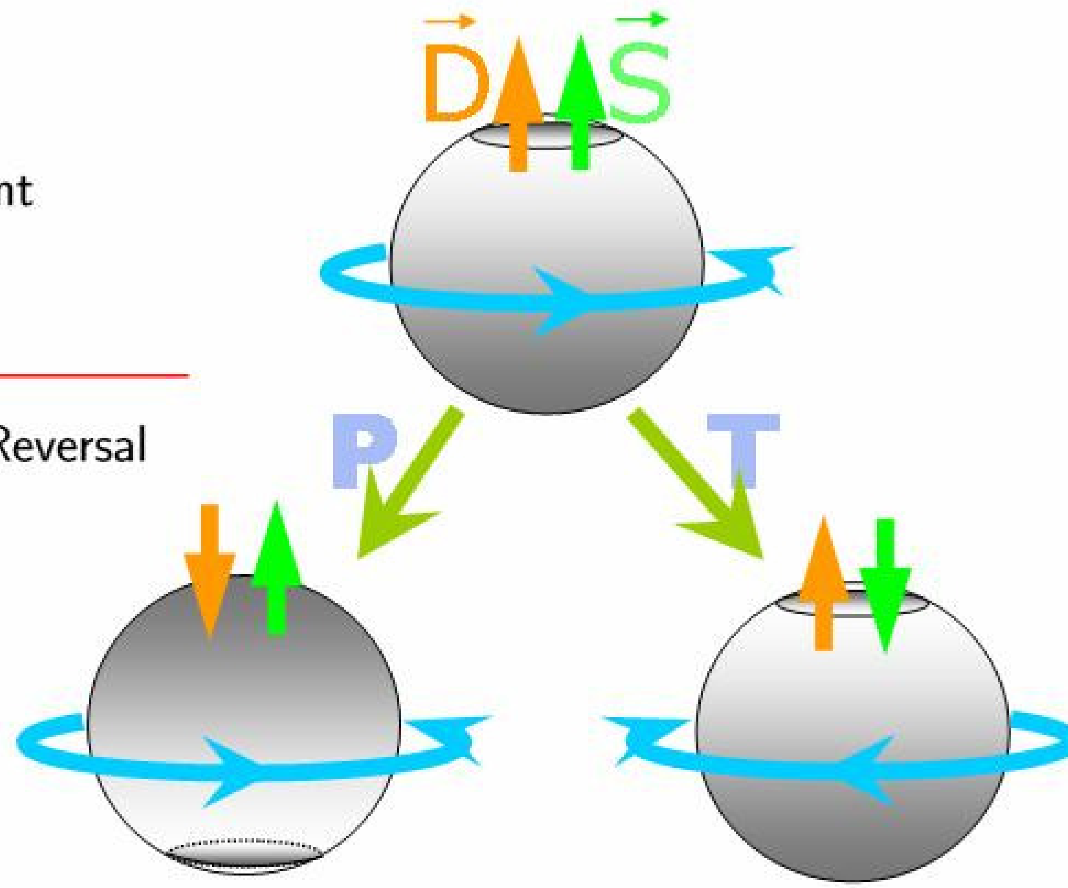
What is a Permanent Electric Dipole Moment (EDM) ?

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

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

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

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



Behavior of Moments under Parity and Time Reversal

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

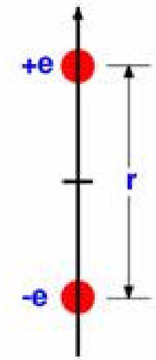
- $H_{\text{Magnetic Dipole}}$ is P-even and T-even
- $H_{\text{Electric Dipole}}$ is P-odd and T-odd !!!

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

Don't Polar Molecules have Electric Dipole Moments ?

Dipole moment of a polar molecule :

$$\vec{d} = \sum e_i \vec{r}_i \;=\; e\, r\, \hat{z} \;\simeq\; \mathrm{e\, a_0} \;\simeq\; 5 \times 10^{-9}\ \mathrm{e \cdot cm}$$



Reconsider the EDM of a polar molecule :

- Dipole moment parallel to internuclear axis ⇒ averaged out by rotation
- Do polar molecules really exhibit a linear Stark shift under $H_{\mathrm{EDM}} = -\vec{d} \cdot \vec{E}_{\mathrm{ext}}$?

$$E'_i = E_i + \langle \Psi_i | H_{\mathrm{EDM}} | \Psi_i \rangle + \sum \frac{|\langle \Psi_j | H_{\mathrm{EDM}} | \Psi_i \rangle|^2}{E_i - E_j} \simeq E_i + \frac{(\vec{d} \cdot \vec{E}_{\mathrm{ext}})^2}{E_i - E_j}$$

$$|\Psi'_i\rangle \approx |\Psi_i\rangle + |\Psi_j\rangle \frac{\langle \Psi_j | H_{\mathrm{EDM}} | \Psi_i \rangle}{E_i - E_j}$$

- Energy eigenstates Ψ_i are eigenstates of parity but $H_{\mathrm{EDM}} = -\vec{d} \cdot \vec{E}_{\mathrm{ext}}$ is P-odd
- $\vec{E}_{\mathrm{ext}}$ field mixes opposite parity states - *induces* dipole, E shift *quadratic* in $\vec{E}_{\mathrm{ext}}$
- No linear Stark shift !

- Only permanent EDM makes mixed parity ground state and *linear* Stark effect

Current Best Limits on Permanent EDMs

⇒ No experimental evidence for a permanent EDM in *any* system

$$\begin{aligned} |d_e| &< 1.6 \times 10^{-27}\ e\ \mathrm{cm} \\ |d_{\mathrm{Hg}}| &< 2.1 \times 10^{-28}\ e\ \mathrm{cm} \\ |d_n| &< 6.3 \times 10^{-26}\ e\ \mathrm{cm} \end{aligned}$$

[1] B.C. Regan *et al.*, Phys. Rev. Lett. **88**, 071805 (2002) (90% C.L.)

[2] M.V. Romalis *et al.*, Phys. Rev. Lett. **86**, 2505 (2001) (95% C.L.)

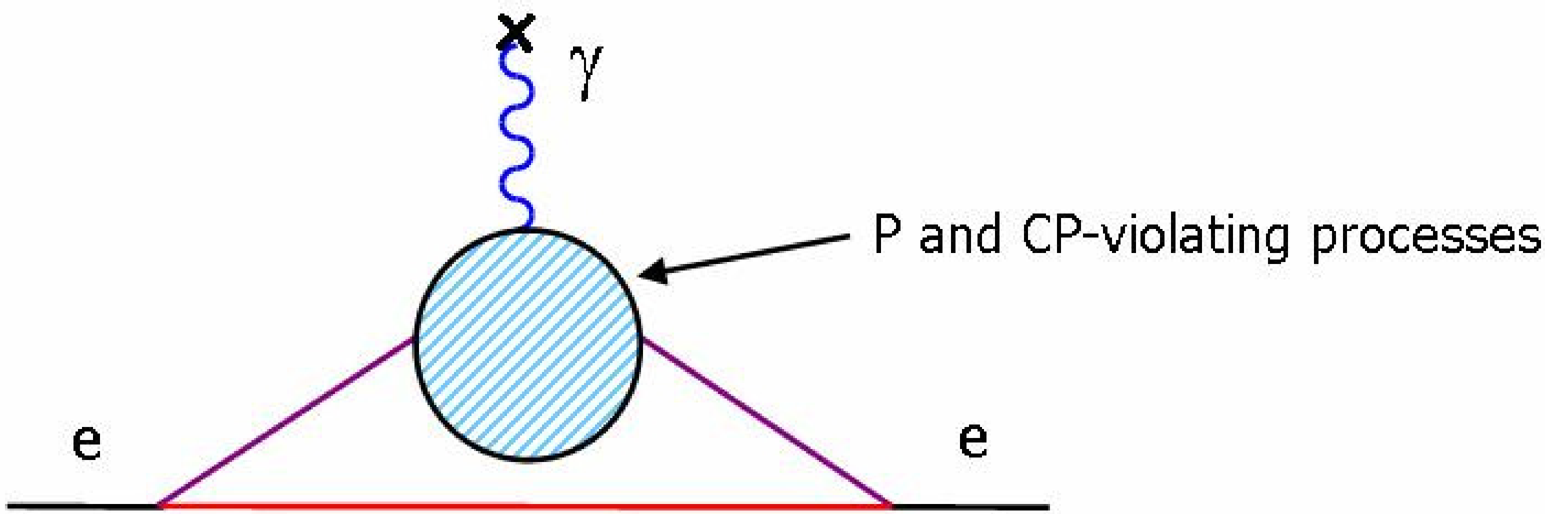
[3] P.G. Harris *et al.*, Phys. Rev. Lett. **82**, 904 (1999) (90% C.L.)

Why do we expect the electron EDM $d_e \neq 0$?

- EDMs violate P, T : through CPT theorem T-violation ⇔ CP-violation
- P-violation observed, CP-violation observed in K and B mesons
- Can generate EDM in SM through radiative corrections

⇒ In same way RC make $g_e \neq 2.0000$, RC can make $d_e \neq 0$

⇒ Construct diagram with enough loops to incorporate P and CP-violating processes



- In SM need at least 4 loops - predicts $|d_e| \leq 1 \times 10^{-40}$ e·cm
- 13 orders of magnitude below current limit $|d_e| < 1.6 \times 10^{-27}$ e·cm !

(B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, Phys. Rev. Lett. **88**, 071805 (2002).)

Why do we expect the electron EDM $d_e \neq 0$?

- SM prediction is so small $\Rightarrow$ any observation $d_e \neq 0$ definitive evidence of new physics

Reasons to expect there is new physics leading to d_e large enough to detect :

- Sakharov showed CP-violation required to generate matter-antimatter asymmetry in universe
  - CP-violation in SM 10^7 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 !

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

$\Rightarrow$ $d_e \neq 0$ definitive evidence of new physics

$\Rightarrow$ Predicted d_e within range accessible to new experiments

$\Rightarrow$ Good time to look for EDMs !

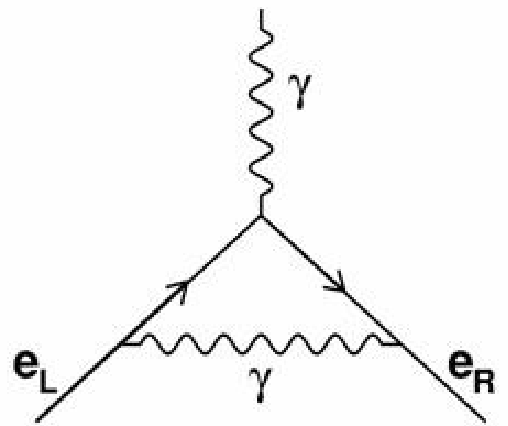
Effective Low Energy MSSM CP-violating Lagrangian

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

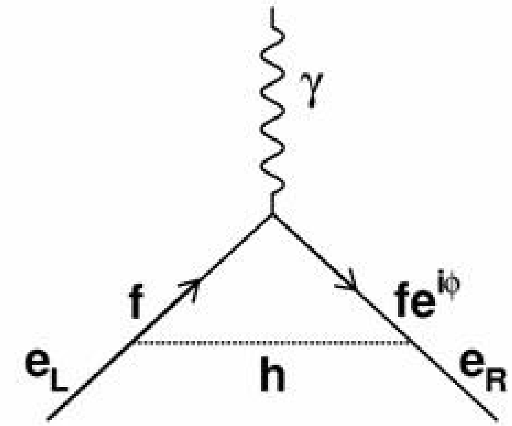
$$\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\bar{\Theta} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3} w f^{abc} G^a_{\mu\nu}\tilde{G}^{\nu\beta,b} G^{\mu,c}_{\beta} - \frac{i}{2}\sum_{i=e,u,d,s} d_i \bar{\Psi}_i \gamma_5 \sigma^{\mu\nu}\Psi_i F_{\mu\nu} - \frac{i}{2}\sum_{i=e,u,d,s} d_i^c \bar{\Psi}_i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

- Contributions : $\bar{\Theta}$, Weinberg 3-gluon, EDMs of e and quarks d_i, chromo-edms of quarks d_i^c
- $|d_{Hg}|$ limits $\rightarrow$ $\bar{\Theta} < 1.5 \times 10^{-10}$, *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 : $w,\ d_{u,d,s},\ d^c_{u,d,s} \Rightarrow d_n$
  - $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u$
  - $d_n = \eta(\Delta_d d_d + \Delta_u d_u + \Delta_s d_s)$, ...
- Experimental limits interpreted in terms of these parameters
  - d_e "easily" extracted from EDM, d_A, observed in atom or molecule

Crude Estimation of an EDM



$\Longleftrightarrow$



⇒ Energy shift from anomalous mag. moment

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

⇒ Energy shift from an electric dipole moment

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

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

We can expect $\sin(\phi) \approx 1$, so ...

$$\Rightarrow d_e \approx \frac{1}{137\cdot 4\pi}\,\frac{1.05\times 10^{-27}}{2\cdot 9.1\times 10^{-28}\cdot 3\times 10^{10}}\,(0.5\times 10^{-5})^2 \left(\frac{100\ \mathrm{GeV}}{m_h}\right)^2\ e\cdot\mathrm{cm} \approx 5\ \times\ 10^{-25}\left(\frac{100\ \mathrm{GeV}}{m_h}\right)^2\ e\cdot\mathrm{cm}$$

Two Loop Contributions to EDMS in SUSY

(From D. Chang, W.Y. Keung, and A. Pilaftsis, Phys. Rev. Lett. **82**, 900 (1999))

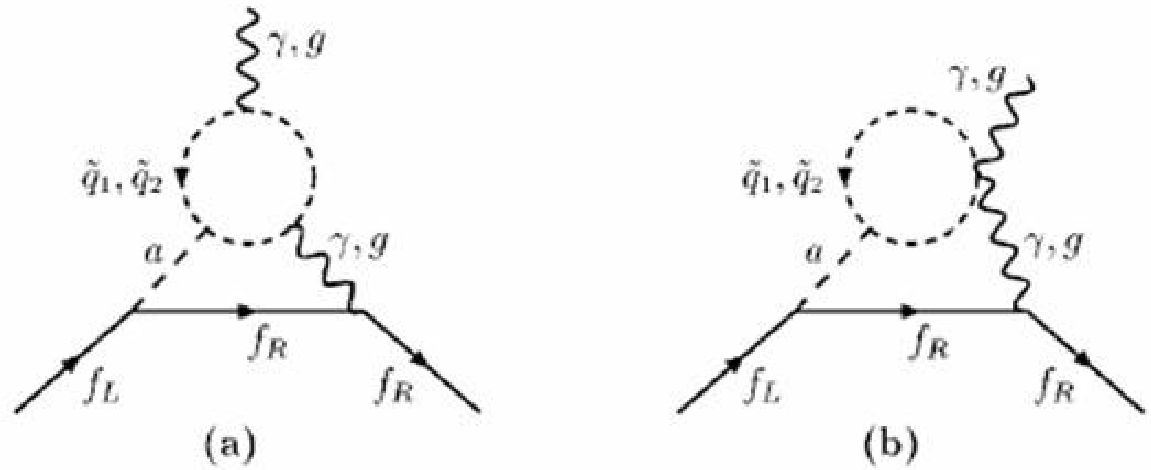
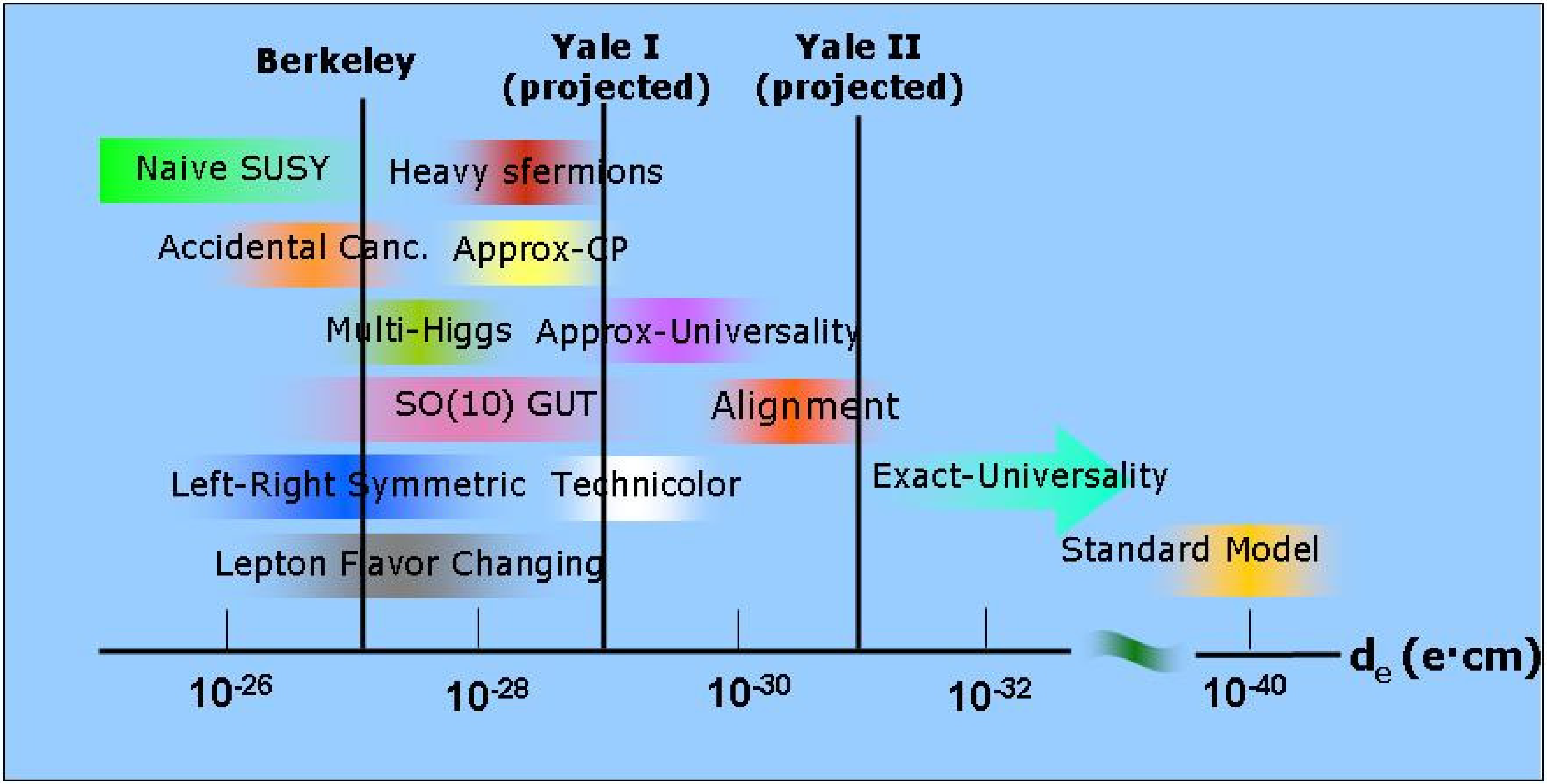


FIG. 1. Two-loop contribution to EDM and chromo-EDM (CEDM) in supersymmetric theories (mirror graphs are not displayed).

$$\left(\frac{d_f}{e}\right)^{\tilde{q}}_{\rm EW} = Q_f \frac{3\alpha_{\rm em}}{64\pi^3}\frac{R_f m_f}{M_a^2} \times \sum_{q=t,b} \xi_q Q_q^2 \left[F\left(\frac{M_{\tilde{q}_1}^2}{M_a^2}\right) - F\left(\frac{M_{\tilde{q}_2}^2}{M_a^2}\right)\right]$$

$R_f = \tan\beta$, F=two-loop function, ξ=CP violating parameter

Searching for new physics with the electron EDM

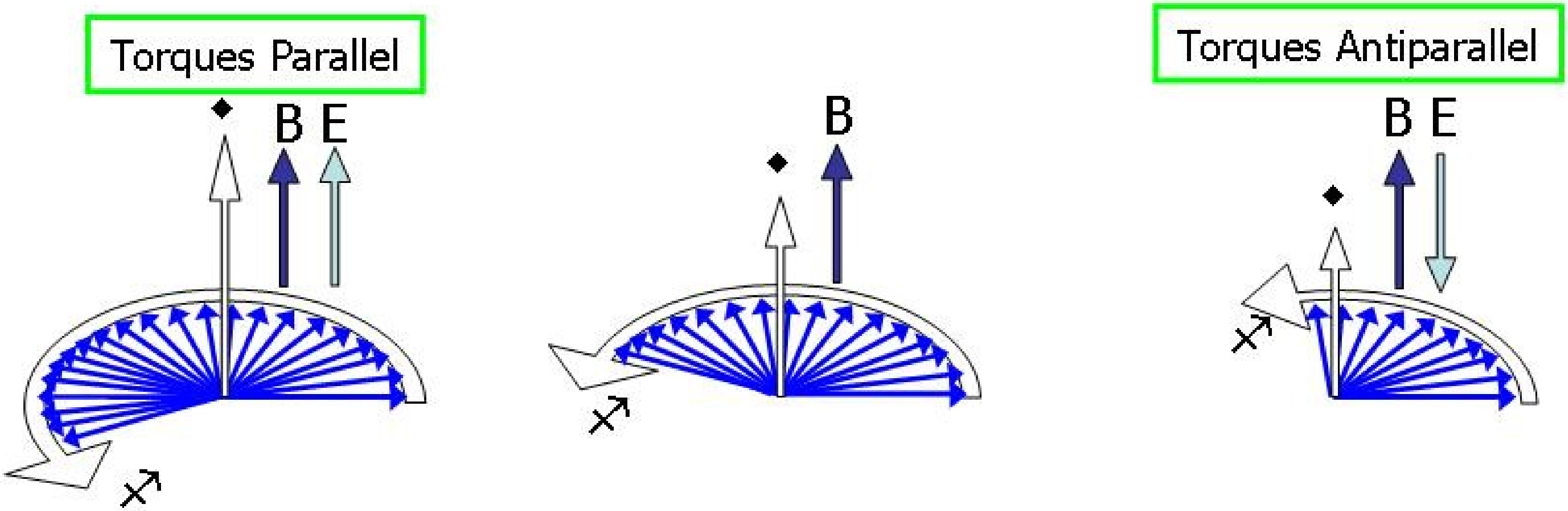


Experimental limit: $|d_e| < 1.6\times10^{-27}$ e·cm (Berkeley)

- d_e is a powerful probe for new physics
- even a null result is interesting

Algorithm for finding an EDM

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



Spin Up

Spin Down

☟E=2❍B+2dE

☟E=2❍B

☟E=2❍B-2dE

- Look for precession frequency shift ☟■”▤dE/h
- For E=100 kV/cm, $d_e=1x10^{-27}$e cm ⏻ ☟■”20 nHz ⑩ ☟B ~ few x 10^{-14}G
- Only works for neutral systems

LANL/SNS Neutron EDM Experiment (M. Cooper, S. Lamoreaux)

- One of 3 new neutron EDM experiments (SNS,ILL,PSI)
- Aims for 2 orders of magnitude improvement $d_n \approx 6 \times 10^{-26}$ e cm $\Rightarrow$ 6×10^{-28} e cm.

Strategy

- Make mixture of neutrons in superfluid ^{4}He at 300 mK, $\rho \approx 2.2 \times 10^{22}$ cm^{-3}
- Impose external $\mathbf{B}_0$ to precess n spins in plane $\perp$ to $\mathbf{B}_0$
- Impose external $\mathbf{E}_0 \parallel$ to $\mathbf{B}_0$
- Measure n precession frequency, flip $\mathbf{E}_0$, look for difference :

$$h\nu_n = -2\mu_n B_0 \pm 2d_n E_0 \Rightarrow h\nu_n = -2\mu_n B_0 \mp 2d_n E_0 \Rightarrow |\Delta\nu| = 4d_n E_0/h$$

What's so hard about that?

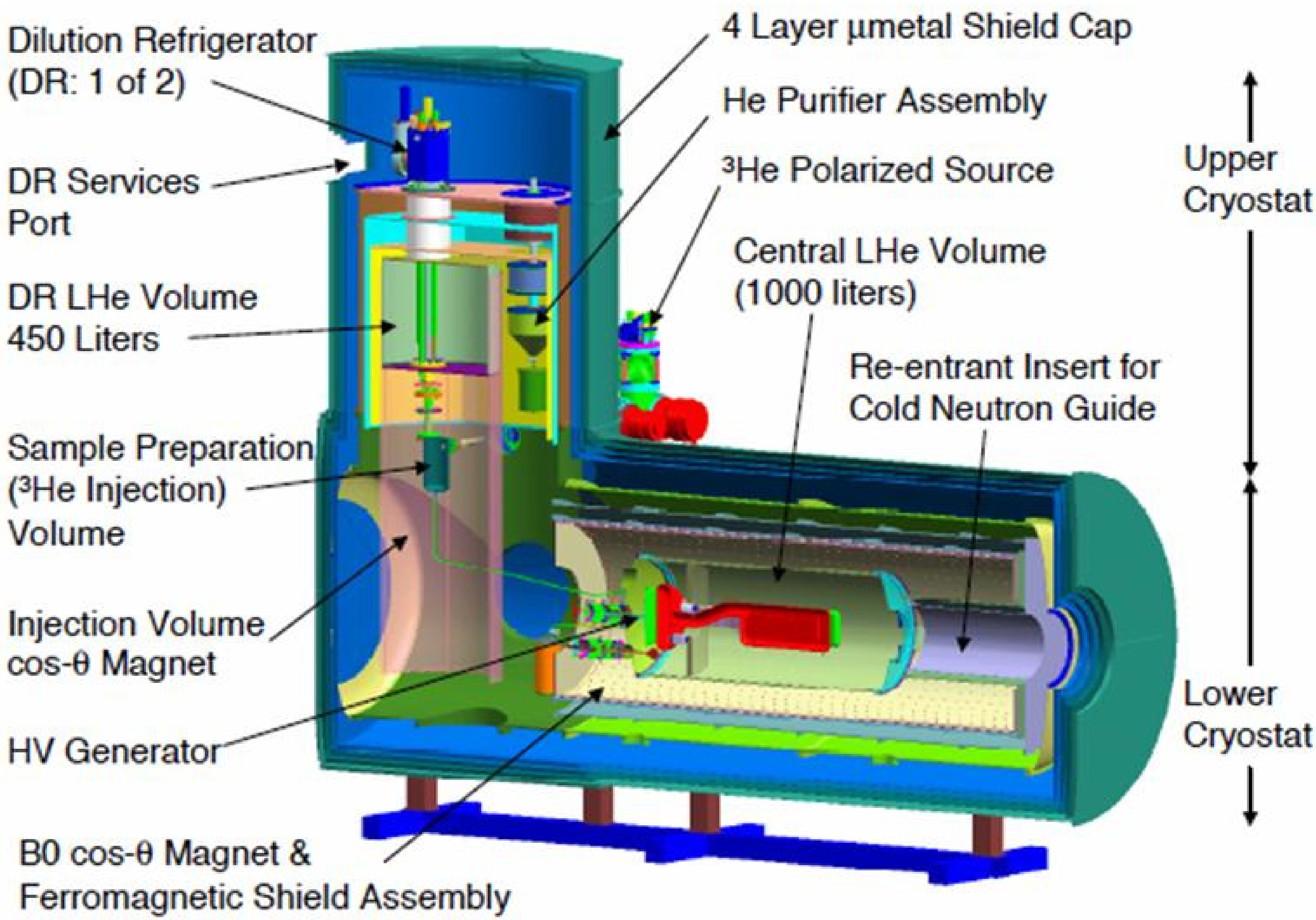
- $\mathbf{B}_0 \approx 1$ mG, $\mathbf{E}_0 \approx 50$ kV/cm, $d_n = 4 \times 10^{-27}$ e cm $\Rightarrow \Delta\nu = 0.19\mu$Hz (<1 ppm of ν_n)
- Record setting UCN density would be 500 cm^3 : in 2 cells of 4000 cm^3, only 4×10^6 neutrons/measurement cycle
- How do you measure spin precession rate of 4 million neutrons?

LANL/SNS Neutron EDM Experiment

What's so hard about that?

- How do you measure spin precession rate of 4 million neutrons?
- Mix in polarized ^{3}He at density 0.85×10^{12} cm^{-3}
- n+^{3}He→p+t+764 keV sensitive to relative spin orientations of n, ^{3}He : when n, ^{3}He spins antiparallel $\sigma \approx 2.4 \times 10^6$ Barns (v ≈ 500 cm/sec)
- $I_{\text{scint}}(t) = I_{\text{bkd}}(t) + N_0 \exp(-\Gamma_{ave} t) \left[\frac{1}{\tau_\beta} + \frac{1}{\tau_{^3He}} P_{^3He} P_n \cos(2\pi(\nu_{^3He} - \nu_n)t + \phi)\right]$
- Use SQUIDS to measure $\nu_{^3He} \approx$ 3 Hz, scintillation determines $\nu_{^3He} - \nu_n \approx$ 0.3 Hz
  $\Rightarrow \delta d_n \approx 7 \times 10^{-26}$ e cm/cycle
- New techniques to improve sensitivity :
  - Improved UCN storage time $\times 10$
  - Improved number of stored UCN $\times 1000$
  - Increased electric field strength $\times 5$ (≈ 50 kV/cm)
  - Efficient detection scheme
- Good control of systematics :
  - Uses ^{3}He co-magnetometer (sensitive to $\mathbf{B}$, but not d_n)
  - $\mathbf{B}$ field measurement with SQUIDs *and* RF spin-dressing technique

LANL/SNS Neutron EDM Apparatus



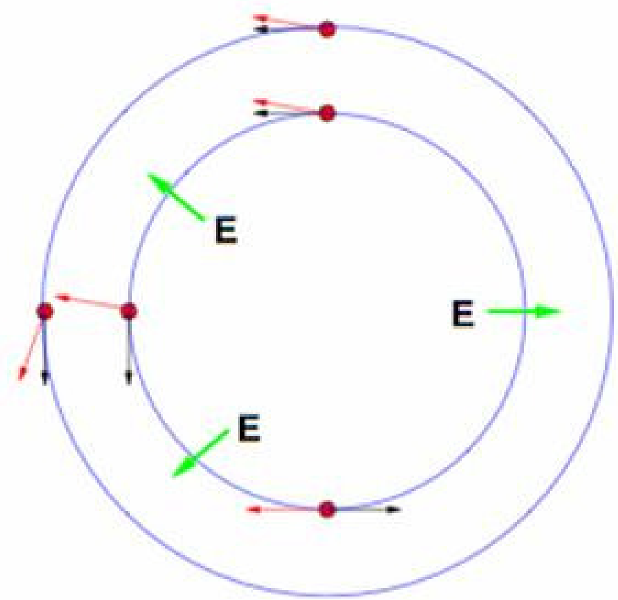
Deuteron EDM in a Storage Ring (Y. Semertzidis, BNL)

- In storage ring, vertical magnetic field $\Leftrightarrow$ radial electric field in particle frame
- Radial electric field exerts torque on EDM, spin precesses out of storage ring plane
- 3.1 GeV muons in 1.5 T field $\rightarrow$ few MV/cm radial electric field

Big Problem + 1 Solution

- $\tau \approx d\mathbf{s} \times (\mathbf{v} \times \mathbf{B}) = -d\mathbf{B}(\mathbf{s} \cdot \mathbf{v}) + d\mathbf{v}(\mathbf{s} \cdot \mathbf{B})$
- For g≠2, spin and cyclotron frequencies different : $\langle \mathbf{s} \cdot \mathbf{v} \rangle \approx 0$

- For deuteron, a=-0.143, spin lags momentum
- Add radial electric field : pushes deuteron out, lengthens cyclotron period $\omega_{\rm spin} = \omega_{\rm cyclotron}$
- Difficult experimentally : need precise alignment of electrodes



Deuteron EDM in a Storage Ring (Y. Semertzidis, BNL)

Better Solution

- Problem was spin and velocity precession frequencies different :

  Spin projection in direction of motion : $S_{\mathrm{L}}(t) = S_{\mathrm{L}}^{0} \cos(\omega_a t + \phi)$

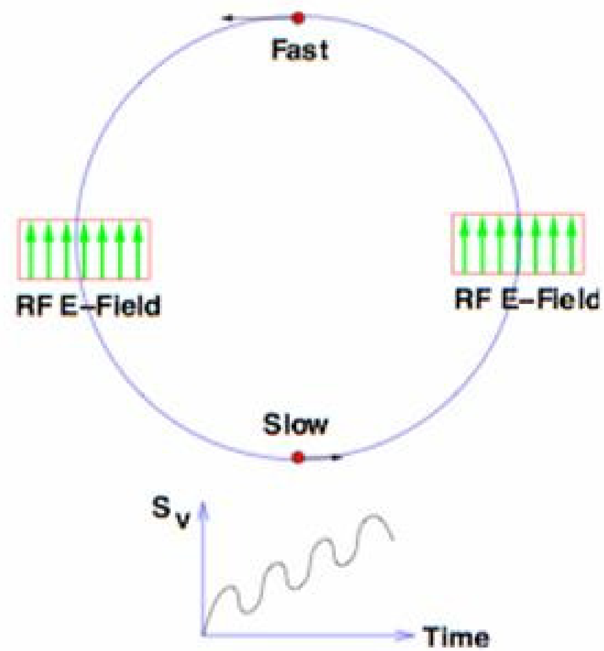
  Velocity projection in direction of motion : $V_{\mathrm{L}}(t) = V^{0}$

  $\Rightarrow \langle \mathbf{s} \cdot \mathbf{v} \rangle \approx 0$

- If we modulate velocity (Y. Orlov) : $V_{\mathrm{L}}(t) = V^{0} + \Delta v \cos(\omega_{\mathrm{L}} t + \alpha)$

$\Rightarrow \langle \mathbf{s} \cdot \mathbf{v} \rangle \approx \langle \cos(\omega_a t + \phi) \cos(\omega_{\mathrm{L}} t + \alpha) \rangle \neq 0$ for $\omega_{\mathrm{L}} = \omega_a,\ \alpha = \phi$

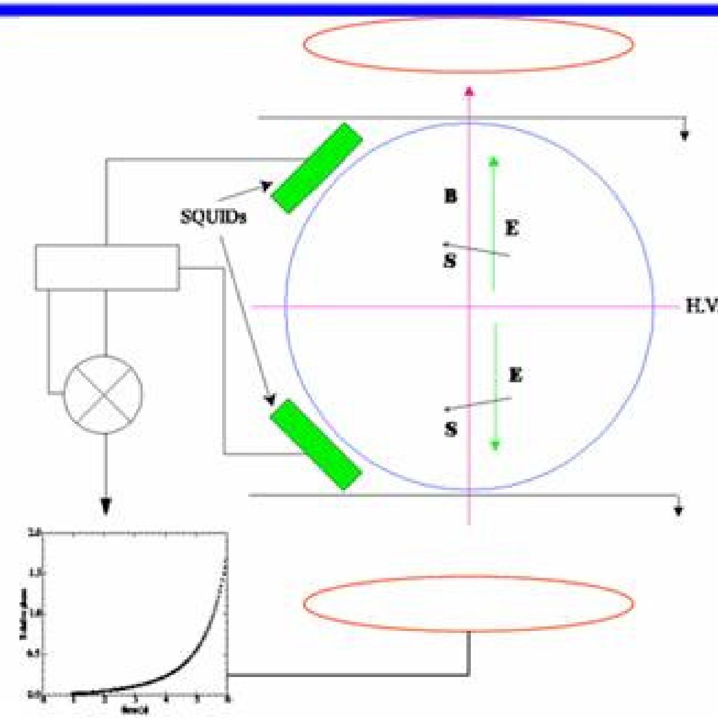
- Spend more time with $\vec{v}$ and $\vec{s}$ parallel than antiparallel
- Net torque on EDM is non-zero, spin acquires component out of storage ring plane
- Could push d_d to level of 10^{-29} e cm.



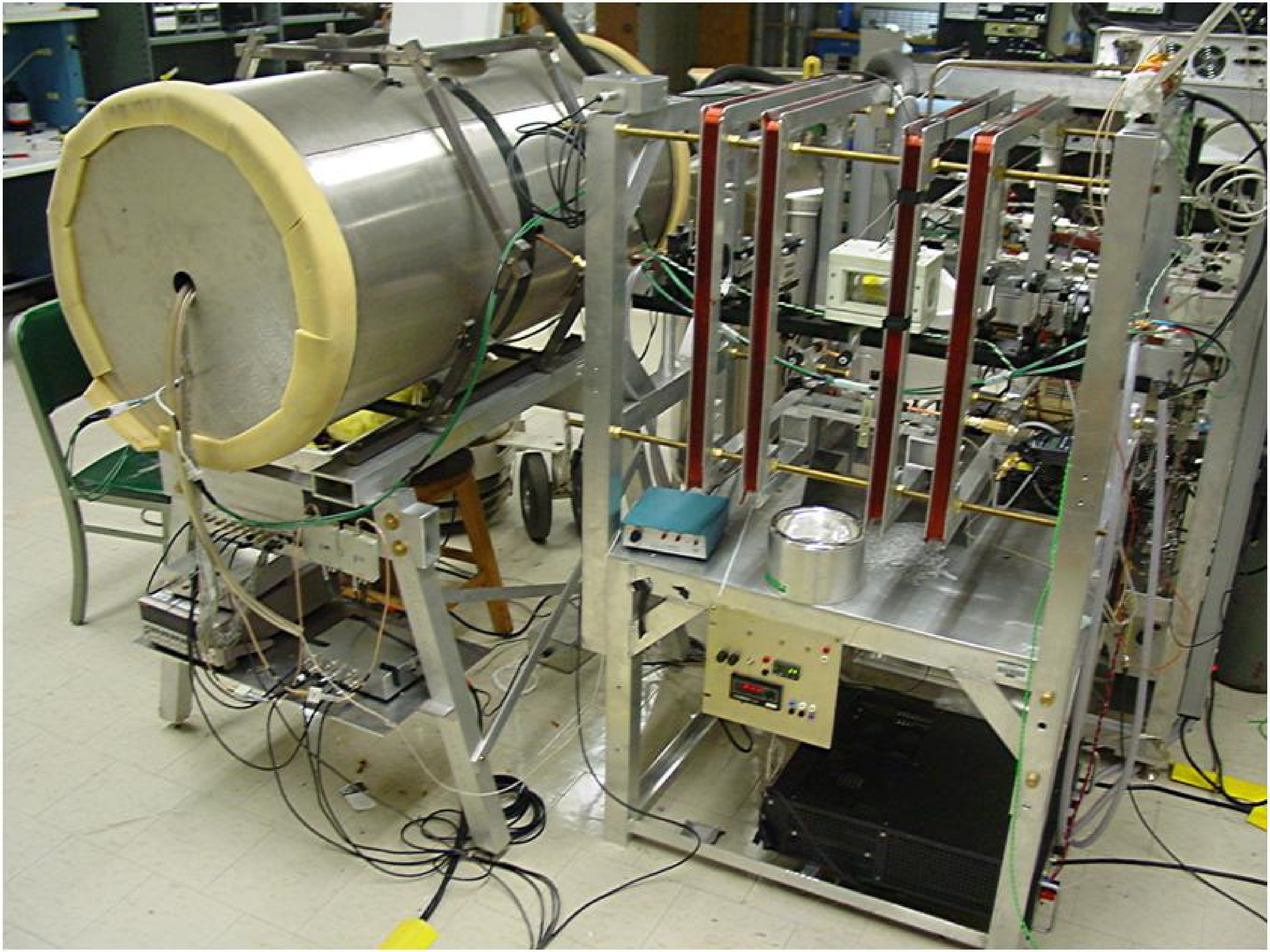
Nuclear EDM using Liquid ^{129}Xenon (M. Romalis, Princeton)

- Optical pumping of Rb + spin exchange = polarized ^{129}Xenon
- Condense xenon to obtain high density 10^{22} cm^{-3} (factor 10^{8} versus ^{199}Hg)
- Long transverse spin lifetime T_2 1300 sec (factor 10 versus ^{199}Hg)
- High electric field breakdown strength $\approx$ 400 kV/cm (factor 50 versus ^{199}Hg)
- Use SQUIDs for magnetometry and detection of xenon nuclear precession
- ^{129}Xe intrinsically 10 times less sensitive than ^{199}Hg

Shot-noise in 1 day $\approx 10^{-36}$ e cm, 10^{-31}-10^{-32} e cm realistic !



Nuclear EDM using Liquid ^{129}Xenon (M. Romalis, Princeton)

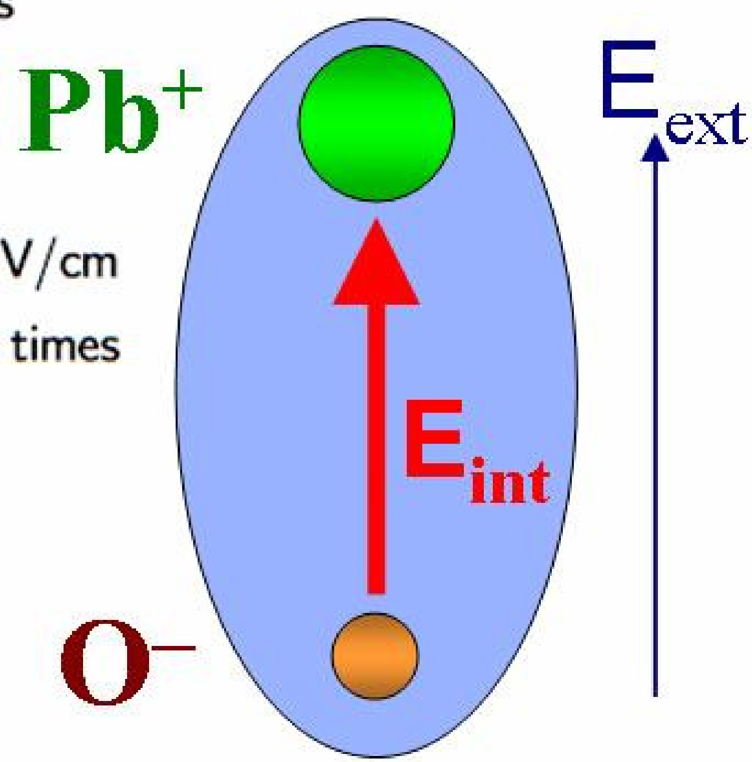


Search for the Electron EDM in Metastable PbO (D. DeMille, Yale)

⇒ Polar molecules with heavy atom & unpaired spin good candidates for d_e search
⇒ Valence electron feels $E_{\rm int} \approx Z^3\alpha^2 e/a_0^2$ along internuclear axis $\hat{n}$
⇒ To harness this : align $\vec{E}_{\rm int}$ along $\vec{E}_{\rm ext}$
⇒ Align electron spin parallel/antiparallel to $E_{\rm int}$ look for energy shift $d_e \times E_{\rm int}$

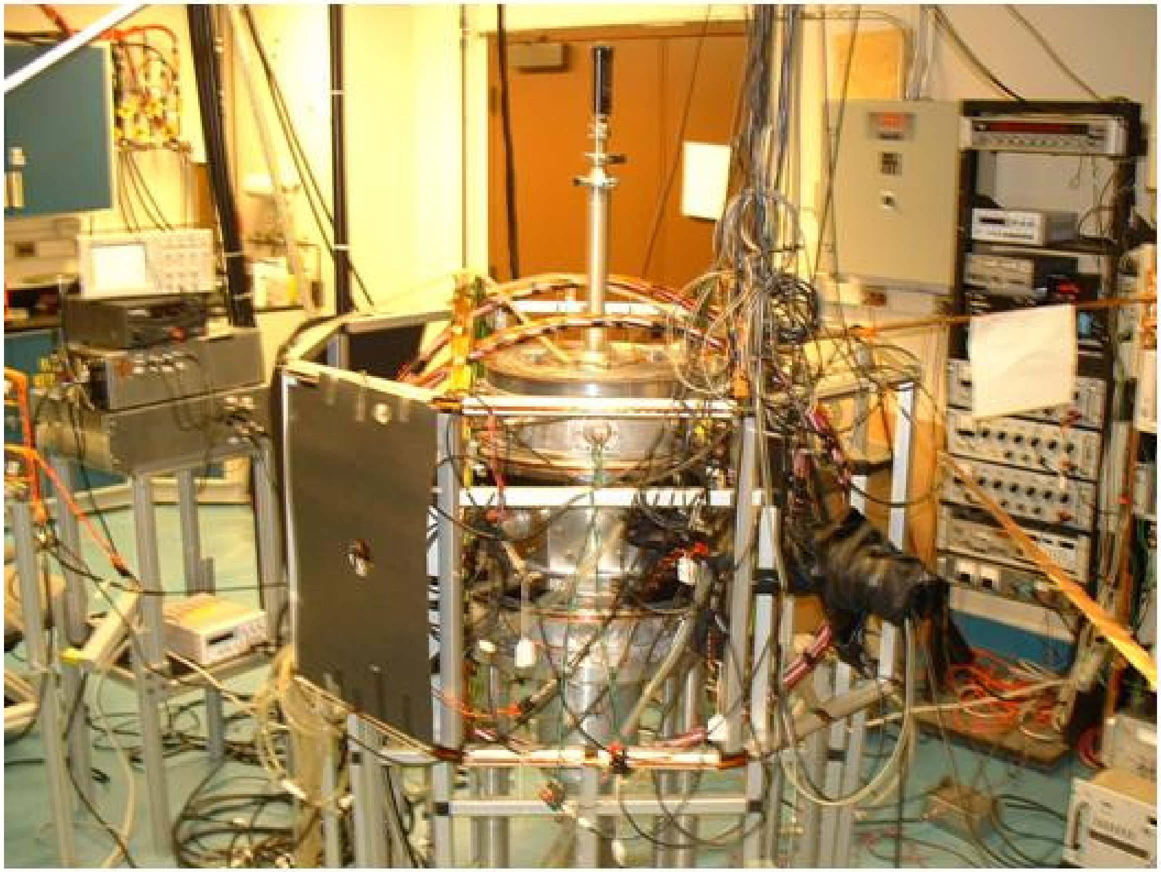
- PbO can be used in a vapor cell ⇒ high count rates
- For PbO* : $E_i - E_j \approx 10$ MHz (Ω-doubling)
- $\vec{E}_{\rm int}$ of PbO* fully polarized along $\vec{E}_{\rm ext} \approx 15$ V/cm
- Valence electron feels $E_{\rm int} \approx Z^3\alpha^2 e/a_0^2 \approx$ 20-60 GV/cm
- Stark shift induced by d_e amplified hundreds of times compared to atoms

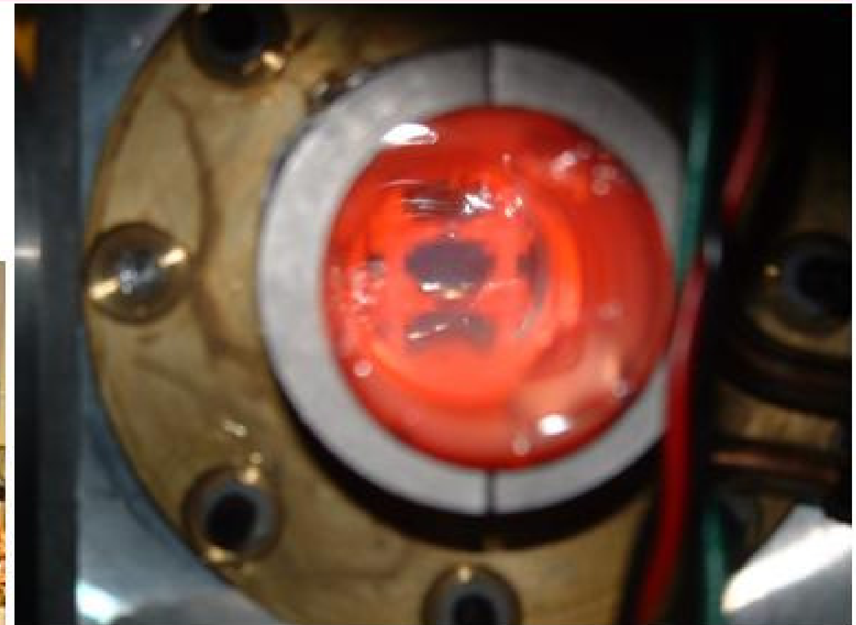
⇒ $d_e \approx 10^{-27}$ e·cm ⇔ 10-30 mHz
⇒ $d_e \approx 10^{-29}$ e·cm ⇔ 100-300 μHz
⇒ Find those shifts !



Concept is simple enough …

- Picture of chamber, leads for oven, RF, electrodes, PMT, B-field coils, …

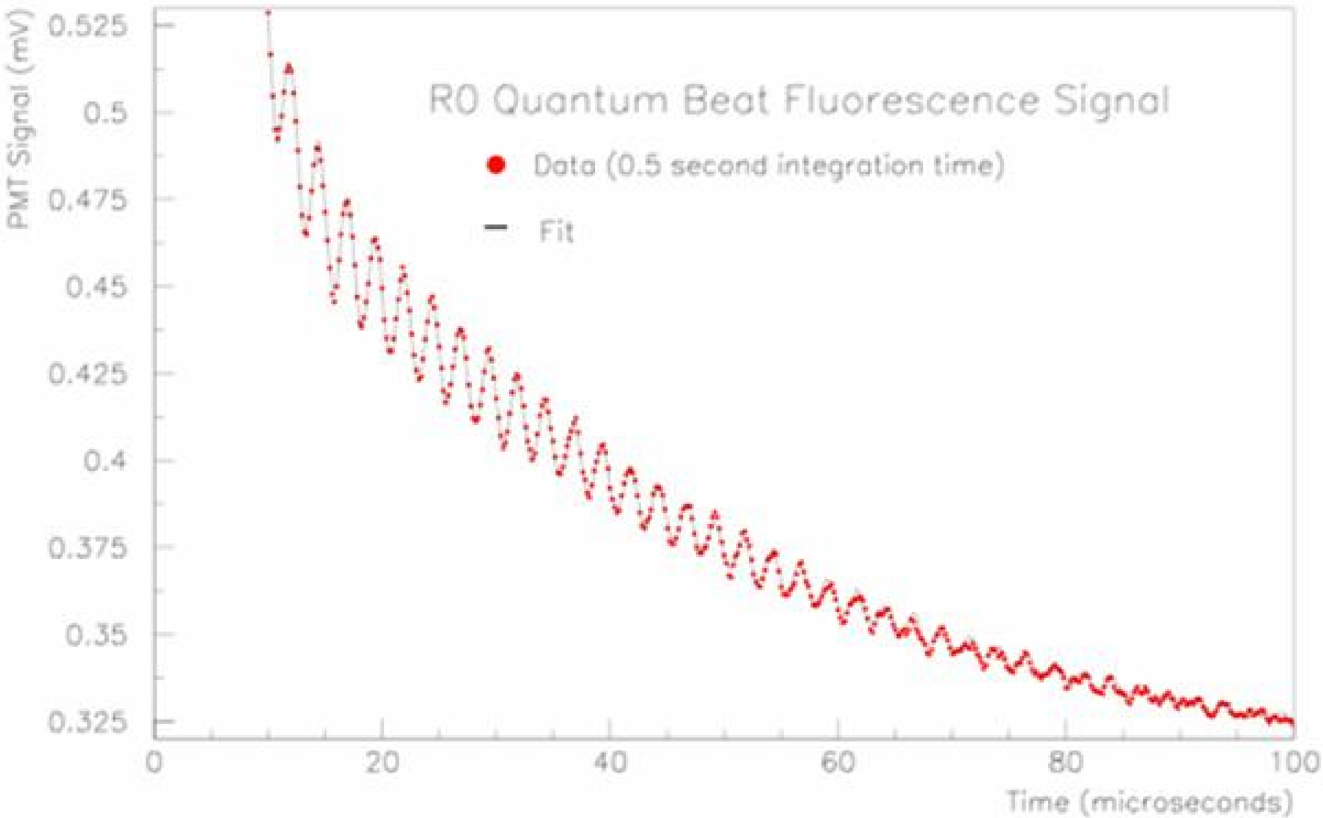




- View down lightpipe

- EDM Cell with electrodes, guard rings

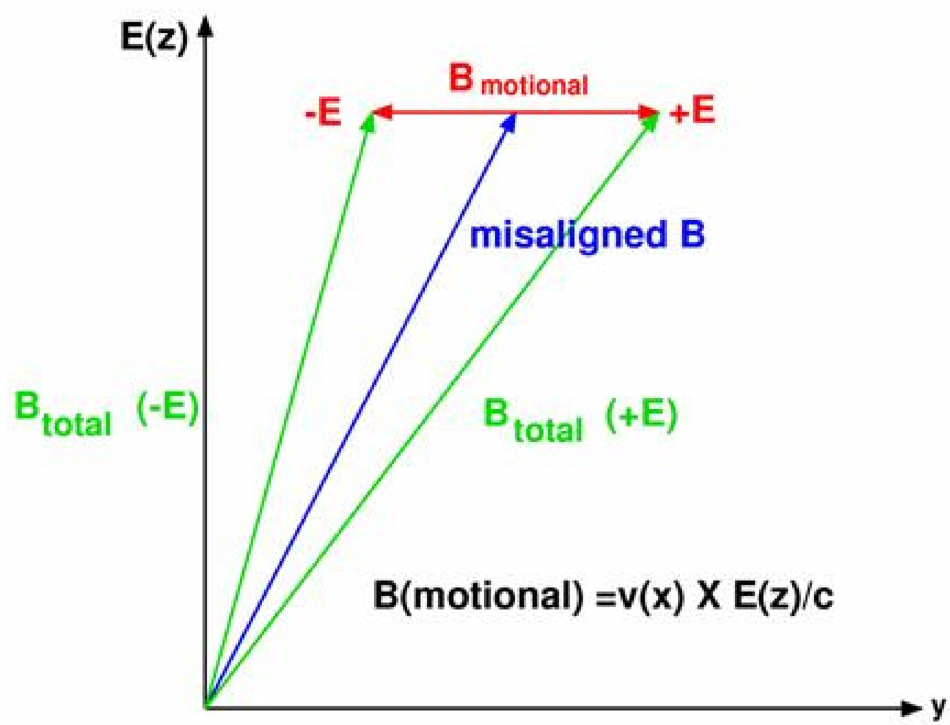
Search for the Electron EDM in Metastable PbO



- Signal $\approx e^{-t/\tau} \times (1 + A\cos(2\pi\nu t + \phi))$
- Spin precession in magnetic and electric fields imprinted on fluorescence signal
- Analyze signals for ν, flip $\mathbf{E}$ or $\mathbf{B}$, look for $\Delta\nu$
- Achieved sensitivity of $\approx 50\mathrm{Hz}/\sqrt{\mathrm{Hz}} \Rightarrow 100\ \mathrm{mHz}/\sqrt{\mathrm{Hz}}$
- Two weeks of running to achieve statistical uncertainty $\approx 10^{-29}$ e cm

Systematic Effects : Motional Magnetic Fields

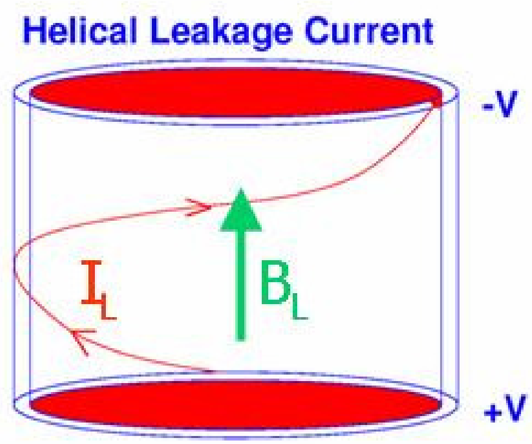
- Motional magnetic fields in the cell $\vec{B}_{\mathrm{motional}} = \frac{\vec{v}}{c} \times \vec{E}$
- If $\vec{B}$ and $\vec{E}$ fields not parallel, get false EDM : $\Delta E \approx \vec{\mu} \cdot \vec{B}_{\mathrm{motional}} \approx \vec{d} \cdot \vec{E}$



- Doesn't cancel in cell : laser excites velocity class Doppler-shifted to resonance
- But effects much less in molecules since $\vec{\mu} \parallel \vec{E} \Rightarrow \vec{\mu} \perp \vec{B}_{\mathrm{motional}} \Rightarrow \vec{\mu} \cdot \vec{B}_{\mathrm{motional}} \approx 0$

Systematic Effects : Leakage Currents

- Consider a leakage current between electrodes : $I_L \approx 1\ \mu$A at $E = 50$ V/cm
- Produces a vertical field $B_L \approx 10^{-7}$ G $\Longrightarrow B_{tot} = B_o \pm B_L$
- Causes beat frequency shift : $\Delta\nu_b \approx \bar{g}\mu_B B_L/h \approx 0.3$ Hz
- Reverses with E, looks like EDM $d_e \approx 10^{-26}\ e\cdot$cm



- Can be suppressed by $\gg 10^3$ by comparing ν_b in Ω-doublets

Summary

- No permanent EDM has been found in any system
- There are good reasons to expect EDMs within range of new generation of experiments
- Non-zero and null results both quite interesting
- New experiments in different systems well underway
- Stay tuned - next 2-5 years will be very interesting

Thanks for your attention!