Limits on CP violation from Electric Dipole Moments

The path from 10^{-24} eV to 100 GeV

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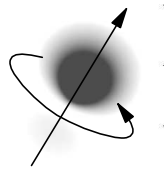
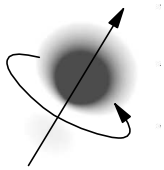
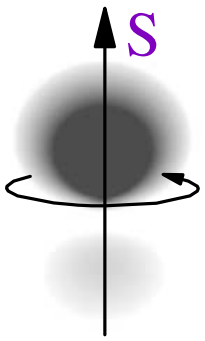


Outline

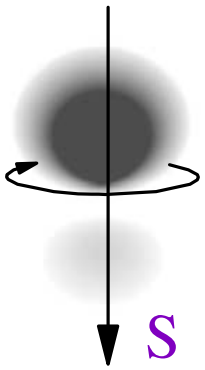
- Basic facts about EDM
- Atomic, Nuclear and QCD physics
  - ⇒Neutron EDM
  - ⇒Atomic EDM → Fermion EDM
  - ⇒Nuclear EDM
- Implications for Extensions of the Standard Model
- Recent experimental progress in EDM searches
  - ⇒Grenoble neutron experiment
  - ⇒Berkeley Tl experiment
  - ⇒Seattle Hg experiment
- Future Directions
  - ⇒ Los Alamos UCN experiment
  - ⇒ Laser cooling and trapping
  - ⇒Search for EDM in polar molecules
  - ⇒Liquid Xe experiment



- Time Reversal Violation:



$$t \rightarrow -t$$
$$\vec{S} \rightarrow -\vec{S}$$
$$\vec{d} \rightarrow \vec{d}$$



$$\vec{d} = d\frac{\vec{S}}{S} \quad d \rightarrow -d \rightarrow 0$$

- CPT Theorem

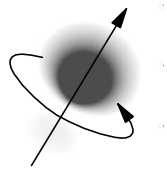
⇩

EDM → T violation ↔ CP violation

- Interaction with electric and magnetic fields:

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\mu, d \sim \frac{e}{M}, \quad \mu_B \sim \frac{e}{1\ \text{MeV}}, \quad d_e < \frac{e}{10^{13}\text{GeV}}$$



- Relativistic form of interaction:

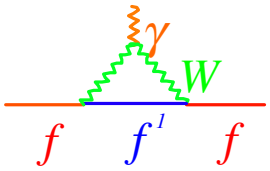
$$\mathcal{L} = d\sigma \cdot \boldsymbol{E} = -\frac{i}{2} d\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi F^{\mu\nu}$$

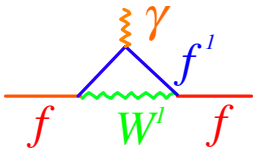
$\Rightarrow$ Complex phases between fields are required

- EDM is induced by loop diagrams

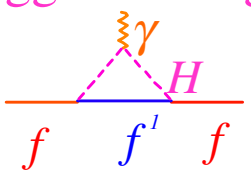
  Lowest order:

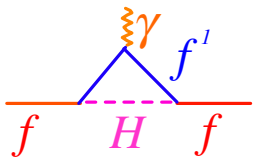
Boson exchange





Higgs exchange





- In Standard Model these and several higher order diagrams cancel!
- In SM EDMs are at least 5 orders of magnitude smaller than present limits

Non-zero EDM gives a background-free signal of CP violation beyond Standard Model

Neutron EDM

- Electric Dipole Moment

  ⇒Non-relativistic SU(6)

$$d_n^E = \frac{4}{3} d_d - \frac{1}{3} d_u$$

  Sea contribution suppressed: $C(\bar{q}\sigma_{\mu\nu}q) = -\bar{q}\sigma_{\mu\nu}q$

  Lattice QCD[1]: $d_n^E = 0.8 d_d - 0.23 d_u$

- Chromo-electric Dipole Moment

$$\mathcal{L} = -\frac{i}{2}\tilde{d}\bar{\psi}\sigma_{\mu\nu}\gamma_5\lambda^a\psi G^{a\,\mu\nu}$$

  ⇒Naive Dimensional Analysis:

$$d_n^C = \frac{e g_s}{4\pi}(O(1)\tilde{d}_d + O(1)\tilde{d}_u) \simeq 0.2\, e\tilde{d}_d$$

  ⇒Chiral perturbation [2]:

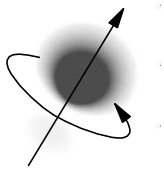
$$d_n^C = e\,(0.7\tilde{d}_d + 0.7\tilde{d}_u + 0.1\tilde{d}_s)$$

d_n^C and d_n^E are comparable, their relative sizes have ~100% uncertainty

[1] S. Aoki *et al.*, Phys. Rev. **D56**, 433 (1997).

[2] I.B. Khriplovich and K.N. Zyablyuk, Phys. Lett. **B383** 429 (1996).

Electron EDM



- Measured in paramagnetic atoms or molecules (Tl, Cs, Fr, YbF, PbO)

  ⇒For purely electrostatic interactions

  $$\langle \vec{E} \rangle = 0 \quad \text{— Shiff shielding}$$

- Heavy atoms:

  ⇒Spin-orbit interaction $\sim (\alpha Z)^2$

  ⇒Nuclear Coulomb field

  $$Ed_a = \frac{\langle s_{1/2}|erE|p_{1/2}\rangle}{E_{s_{1/2}} - E_{p_{1/2}}} \left\langle p_{1/2}|d_e \frac{Ze}{r^2}|s_{1/2}\right\rangle$$

  ⇒Relativistic enhancements

- Thallium atomic EDM gives the best limit

  $$d_{Tl} = -(585 \pm 50)\, d_e$$

Nuclear EDM

- Measured in diamagnetic atoms or molecules (Hg, Xe, TlF)
- Proportional to nuclear "Shiff" moment S –

  Difference between charge distribution and electric dipole moment distribution in the nucleus

$$d_a = R_A\, S$$

  $\Rightarrow R_A$ - from atomic calculations, uncertainty 30% $\rightarrow$ 10%

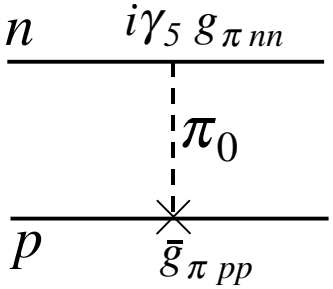
- Shiff moment is produced by $\not{C}\not{P}$ nucleon-nucleon interactions: $\xi_{np}\frac{G_F}{\sqrt{2}}(\bar{p}p)(ni\gamma_5 n)$

$$S = R_N \xi_{np}$$

  $\Rightarrow$ R_N - from nuclear shell model, uncertainty 30%

- $\not{C}\not{P}$ nucleon-nucleon interactions are dominated by Chromo-EDM of the quarks:

$$\bar{g}_{\pi pp} \sim (\tilde{d}_d - \tilde{d}_u)$$

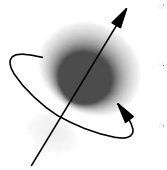


$$d_{Hg} = -0.032\, e(\tilde{d}_d - \tilde{d}_u - 0.012\tilde{d}_s)$$

$\Rightarrow$ Uncertainty in relative coefficients is 20% [1]

[1] T. Falk, K. A. Olive, M. Pospelov, R. Roiban, hep-ph/9904393

Summary of Experimental Limits



- Neutron: $|d_n| < 6.3 \times 10^{-26}$ e cm (90% C.L.) [1]

$$0.8d_d - 0.23d_u + e(0.7\tilde{d}_d + 0.7\tilde{d}_u + 0.1\tilde{d}_s) < 6.3 \times 10^{-26} \text{ e cm}$$

- Electron EDM: $|d_e| < 4 \times 10^{-27}$ e cm (95% C.L.) [2]

$$|d_e| < 7.6 \times 10^{-26} \frac{m_e}{m_d} \text{e cm}$$

- ^{199}Hg Atom: $|d_{Hg}| < 8.7 \times 10^{-28}$ e cm (95% C.L.) [3]

$$e|\tilde{d}_d - \tilde{d}_u - 0.012\tilde{d}_s| < 2.7 \times 10^{-26} \text{ e cm}$$

All three limits are comparable

Constrain different combinations of fundamental EDMs

[1] P.G. Harris *et al.*, Phys. Rev. Lett. **82**, 904 (1999)

[2] E.D. Commins, S.B. Ross, D. DeMille, and B.C. Regan, Phys. Rev. A **50**, 2960 (1994).

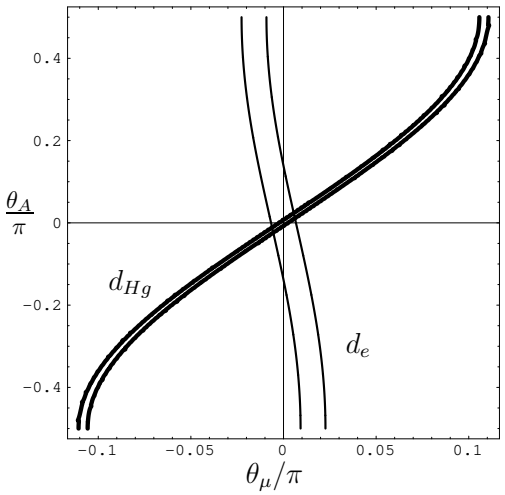
[3] J.P. Jacobs, W.M. Kmipstein, S.K. Lamoreux, B.R. Heckel, and E.N. Fortson, Phys. Rev. A **52**, 3521 (1995).

Limits on Complex phases in Supersymmetry

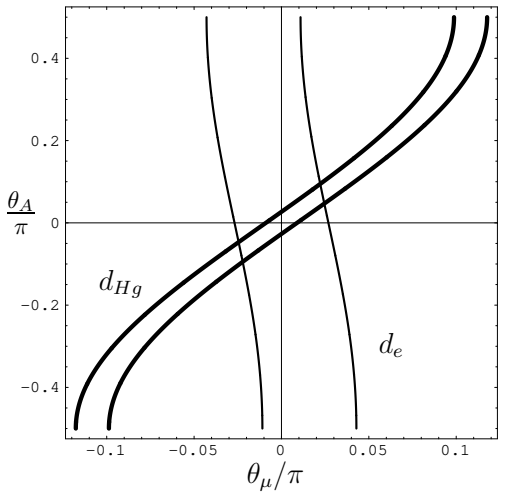
- Simplified SUSY [1]:

  ⇒ All masses scales = M, tanβ = 2

M = 250 GeV



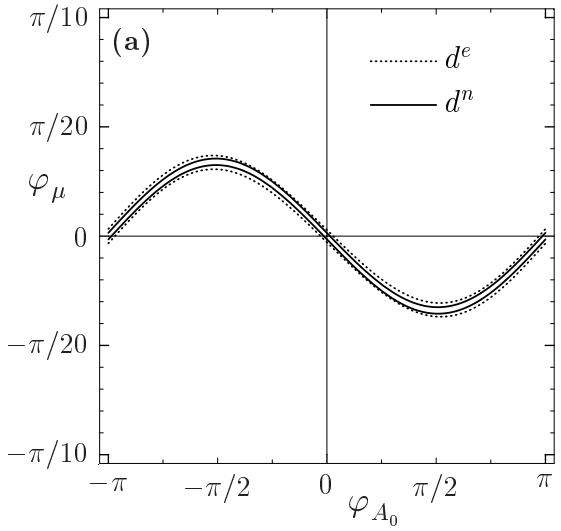
M = 500 GeV



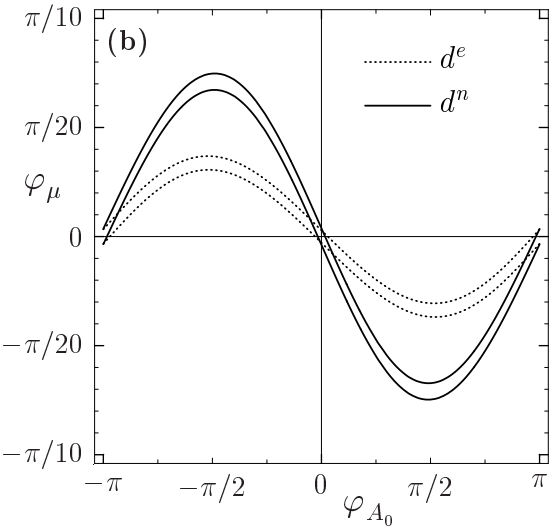
- mSUGRA [2]:

  M_0 = 150 GeV, $M_{1/2}$ = 200 GeV, $|A_0|$ = 450 GeV, tanβ = 3

Quark-Parton Model



Chiral Quark Model

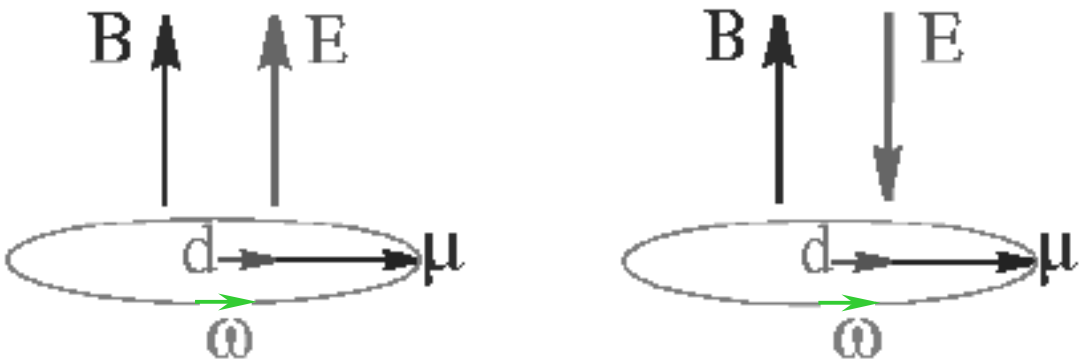


[1] T. Falk, K. A. Olive, M. Pospelov, R. Roiban, hep-ph/9904393

[2] A. Bartl, T. Gajdosik, W. Porod, P. Stockinger, and H. Stremnitzer, hep-ph/9903402

How to detect an EDM

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

Fundamental Limit - Shot Noise

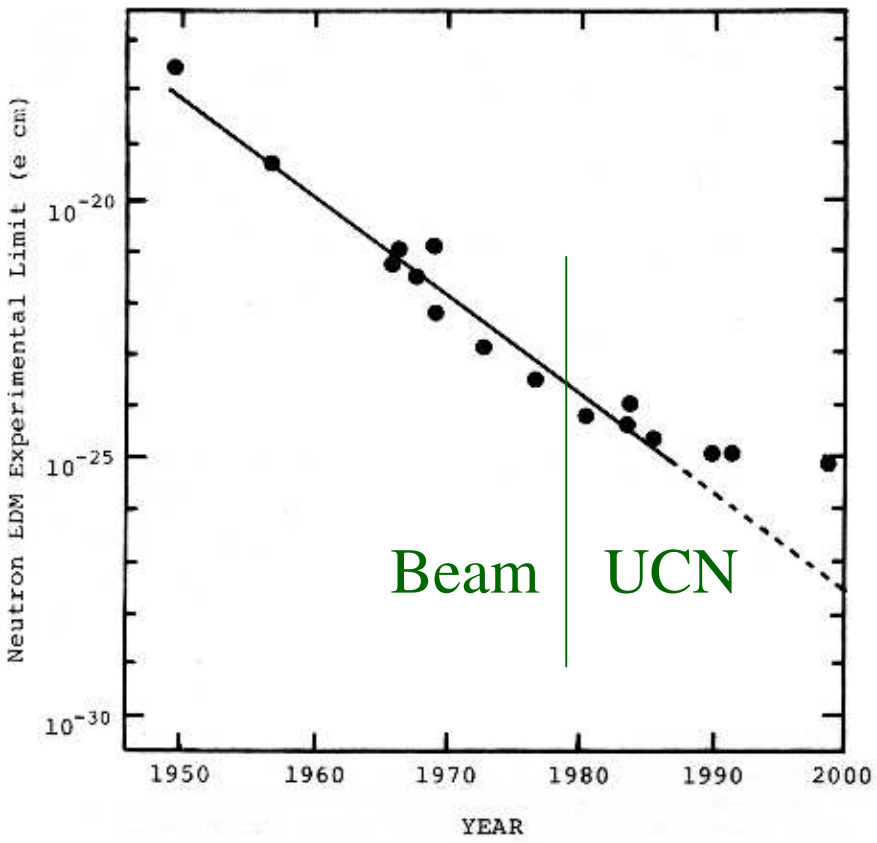
- Single atom with coherence time τ

$$\delta\omega = \frac{1}{\tau}$$

- N uncorrelated atoms measured for time T

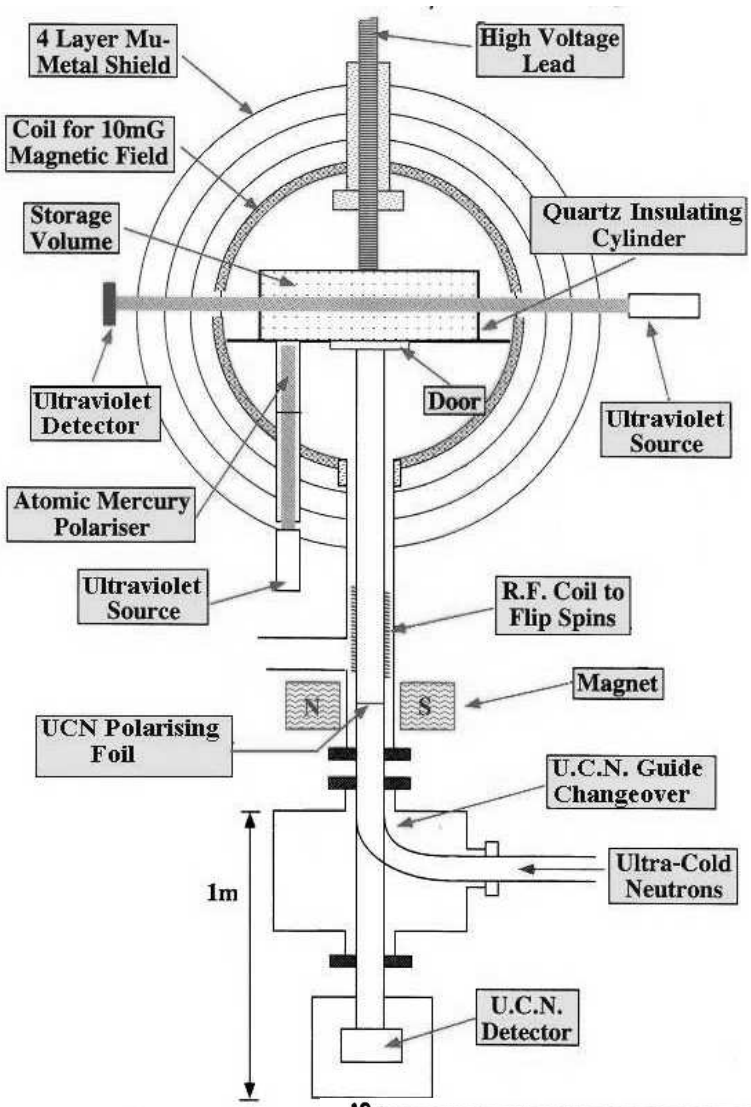
$$\delta\omega = \frac{1}{\sqrt{\tau T N}}$$

Search for EDM of the neutron



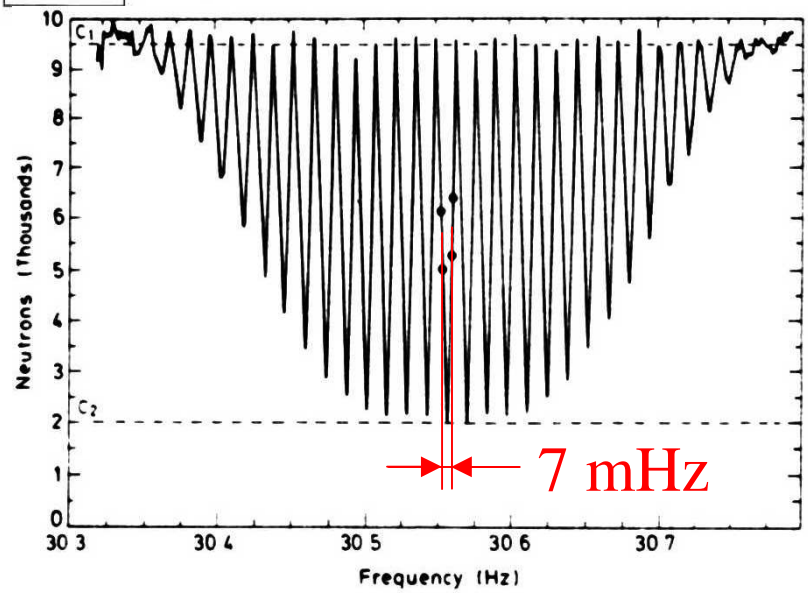
- Ultra-cold neutrons: T ≈ 1 mK, E ≈ 100 neV
  - ⇒ Extracted from Maxwell tail of neutrons moderated to 30K.
  - ⇒ Maximum density obtained is 10 cm^{-3}
  - ⇒ Can be trapped in bottles for ~ 100 sec by Fermi pseudo-potential U ≈ 200 neV

Grenoble Neutron EDM Experiment

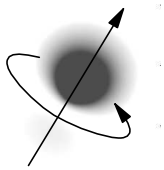


- Ramsey separated field technique
- N = 13,000 neutrons
- Storage time = 130 sec
- E = 4.5 kV/cm
- Main systematic effect: magnetic fields due to leakege currents = 5 nA

  ⇒ Eliminated by ^{199}Hg comagnetometer



"Recent" neutron EDM results



- ILL (Grenoble), 1990 [1]

$$d_n = -(3.4 \pm 2.6\ (\text{stat}) \pm 4.1(\text{sys})) \times 10^{-26} e\ \text{cm}$$

$$|d_n| < 12 \times 10^{-26} e\ \text{cm}\ \ (95\%\ \text{C.L.})$$

- PNPI (Gatchina), 1992 [2]

$$d_n = +(2.6 \pm 4.2\ (\text{stat}) \pm 1.6(\text{sys})) \times 10^{-26} e\ \text{cm}$$

$$|d_n| < 11 \times 10^{-26} e\ \text{cm}\ \ (95\%\ \text{C.L.})$$

- ILL (Grenoble), 1999 [3]

$\Rightarrow$New data (with Hg comagnetometer)

$$d_n = +(1.9 \pm 5.4\ (\text{stat}) \pm 1?(\text{sys})) \times 10^{-26} e\ \text{cm}$$

$$|d_n| < 11 \times 10^{-26} e\ \text{cm}\ \ (95\%\ \text{C.L.})$$

$\Rightarrow$Combined with their 1990 result

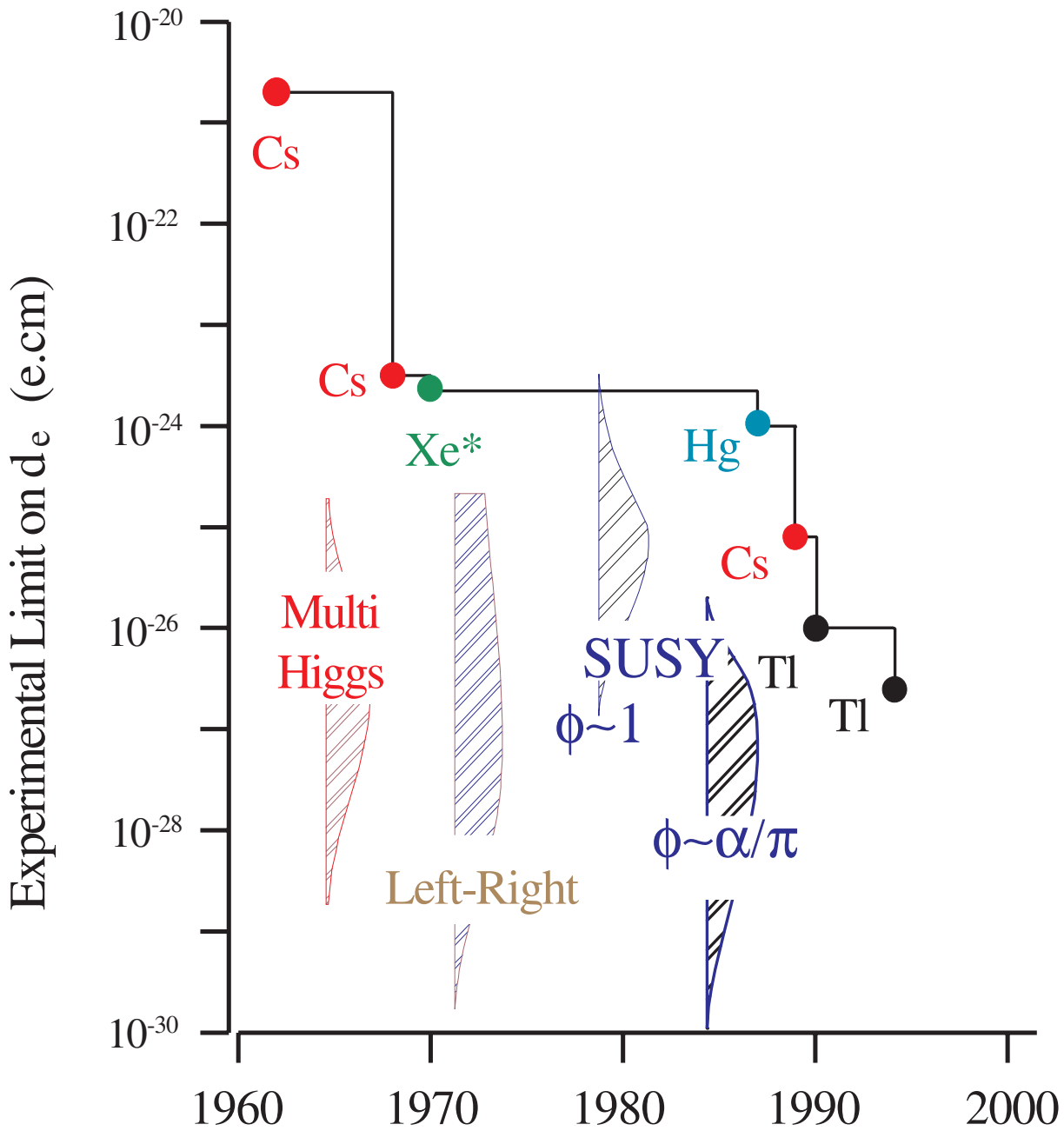
$$d_n = -(1.0 \pm 3.6) \times 10^{-26} e\ \text{cm}$$

$$|d_n| < 6.3 \times 10^{-26} e\ \text{cm}\ \ (90\%\ \text{C.L.})$$

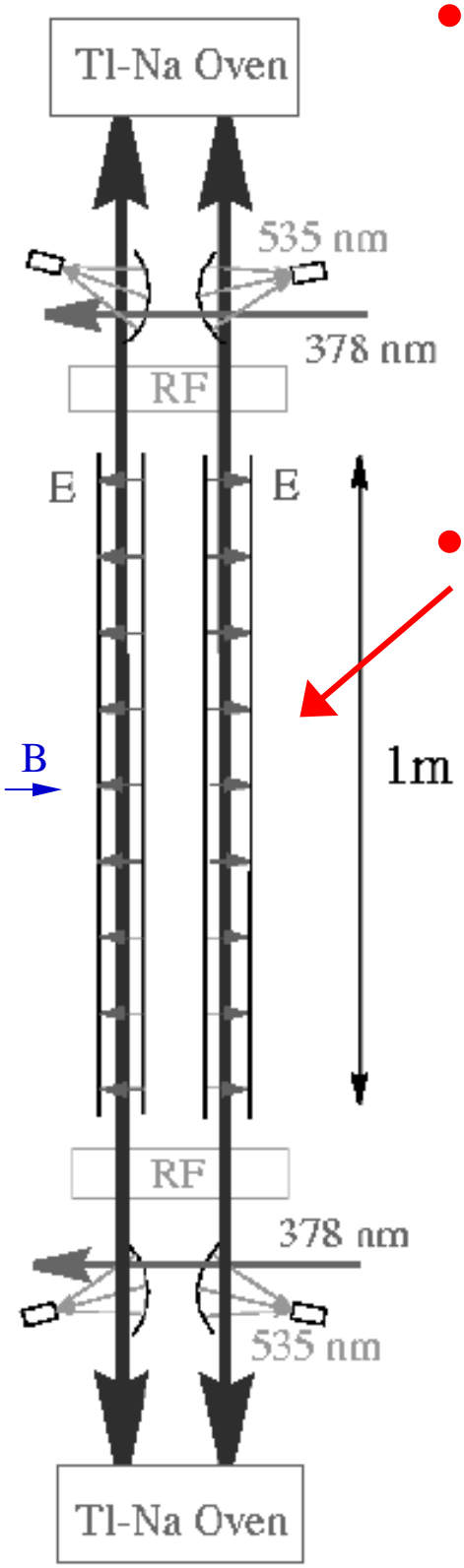
- Should be treated as World average

[1] K.F. Smith *et al*, Phys. Lett. B **234**, 191 (1990)
[2] I.S. Altarev *et al*, Phys. Lett. B **276**, 242 (1992)
[3] P.G. Harris *et al*., Phys. Rev. Lett. **82**, 904 (1999)

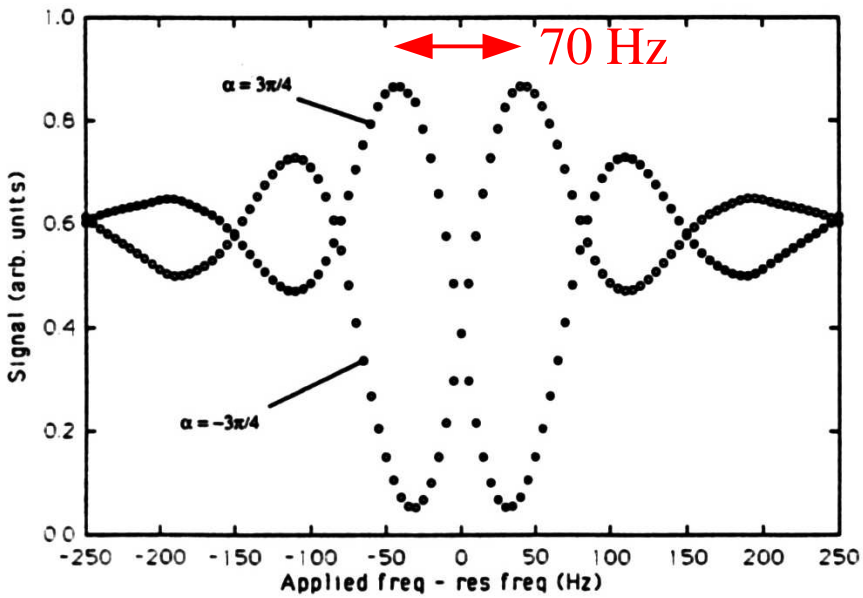
Search for the Electron EDM



Berkeley Tl Experiment

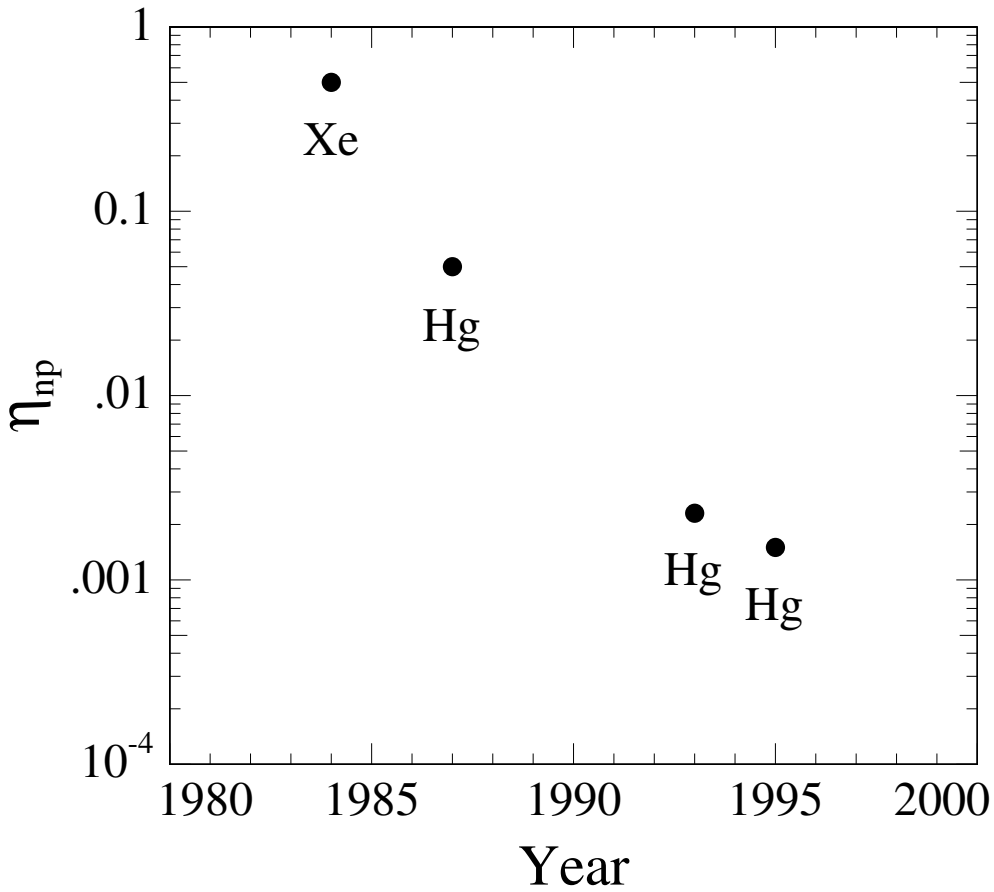


- Classic Ramsey separated field atomic beam apparatus
  - ⇒ Flux = 10^{17} atoms/sec
  - ⇒ Transit time = 2.6 msec
  - ⇒ E = 100 kV/cm
  - ⇒ Major systematic effects:
    - $B_m = v \times E/c$
    - Berry's phase
- Next version of the experiment is build:
  - ⇒ Two pairs of counter-propagating Tl beams
  - ⇒ 4 Na co-magnetometer beams
  - ⇒ Present goal $d_e < 4 \times 10^{-28}$ e cm requires 1 month of integration

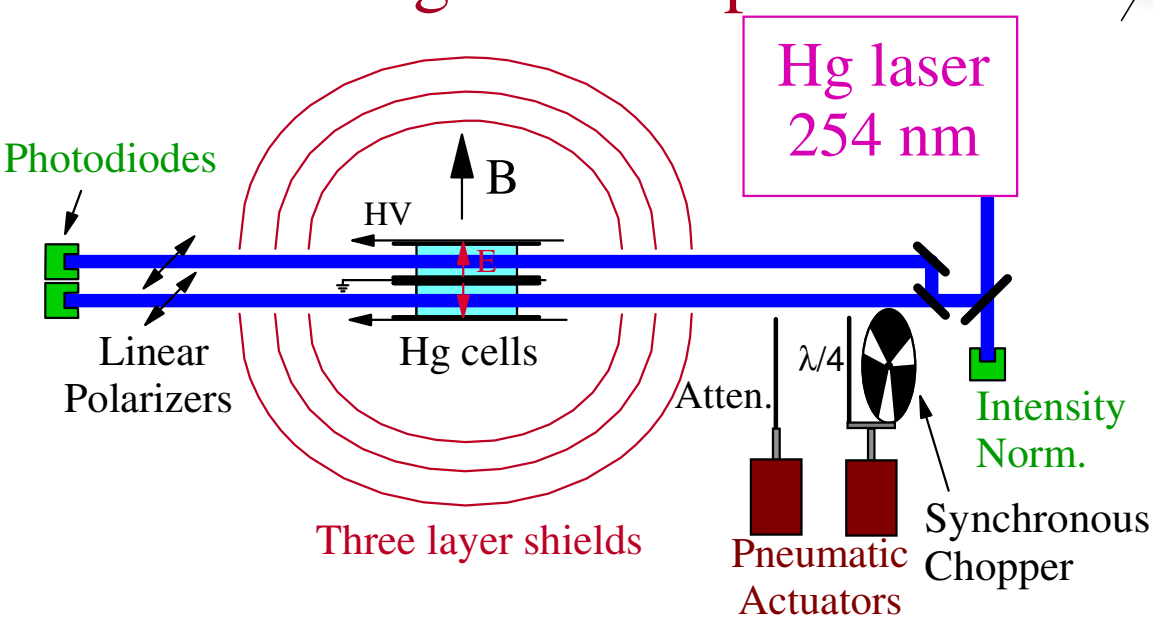


Search for EDM of Diamagnetic Atoms

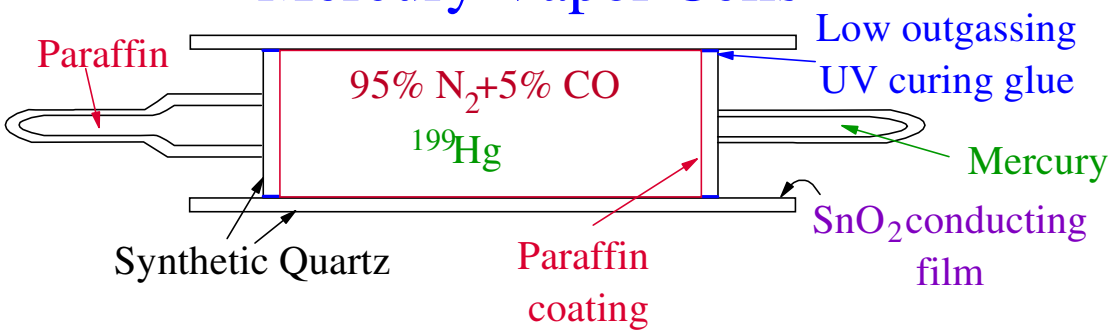
- η_{np} - strength of $\not{C}\not{P}$ n-p interaction



New ^{199}Hg EDM experiment

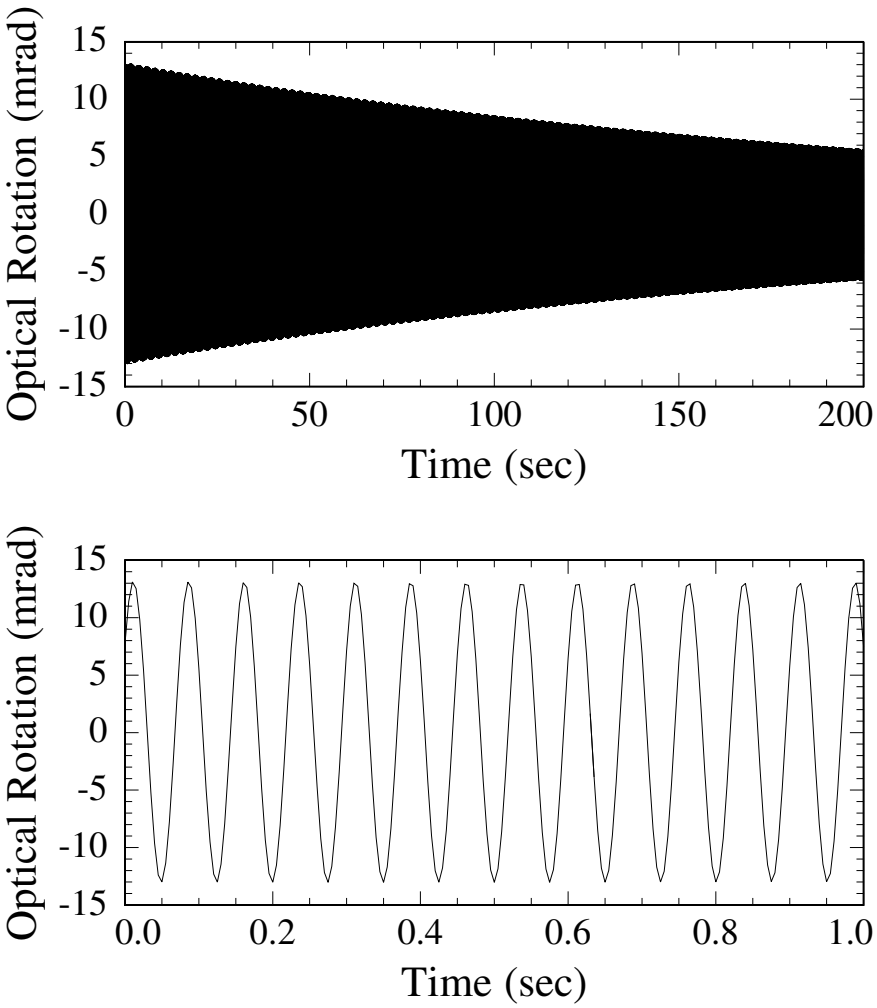


Mercury Vapor Cells



- Classic optical pumping experiment
  - ⇒ N = 2×10^{14} atoms
  - ⇒ Coherence time = 200 sec
  - ⇒ E = 10 kV/cm
  - ⇒ Systematic effects
    - Leakage currents ~ 0.5 pA
    - Effect of electric field on surface relaxation
- Present goal $d_{Hg} < 10^{-28}$ *e* cm requires 10 days of integration

^{199}Hg Precession Data

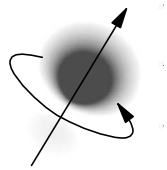


- Fit to decaying exponential gives

  $\sigma(\nu) = 10$ nHz, $\sigma(d_{Hg}) = 10^{-27}$ e cm

1 nHz $= 4\times10^{-24}$ eV

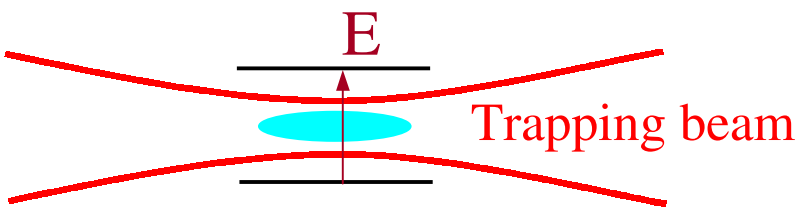
Expected future improvements



- Near future (1-2 years) - existing techniques
  - ⇒Limit on electron EDM reduced by ~10
  - ⇒Limit on Hg EDM reduced by ~10
- Future directions
  - ⇒Los Alamos UCN experiment
    (M. Cooper, S. Lamoreaux)
    - $d_n \sim 10^{-28}$ e cm
  - ⇒Laser cooling and trapping of Cs
    (S. Chu, D. Heinzen, D. Weiss)
    - $d_e \sim 10^{-29}$ e cm
  - ⇒Electron EDM from PbO molecule
    (D. DeMille)
    - $d_e \sim 10^{-29} \rightarrow 10^{-31}$ e cm
    - Self-comagnetometer
  - ⇒Liquid Xe experiment
    (M.R.)
    - $d_{Xe} \sim 10^{-32}$ e cm

Laser cooling and trapping

- Trap cold atoms in vacuum with light and make an EDM measurement:



⇒ Large E field

⇒ Long storage time

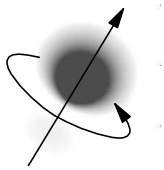
⇒ No $v \times E/c$ effect

⇒ No leakage currents

- Problems

⇒ Cold collision frequency shifts

⇒ Shot noise limit is not very low



Liquid ^{129}Xe

⇑ Ultimate shot noise

⇒ Density 10^{22} cm^{-3}

⇒ Spin lifetime 1000 sec (No surface coatings!)

⇒ Electric field breakdown 400 kV/cm

⇓

$$\delta d_{Xe} = 6 \times 10^{-37} \text{ e cm in 1 day}$$

⇓ Sensitivity to $\not{C}\not{P}$ interactions smaller by a factor of 10 compared with Hg.

⇑ Liquid Xe can be polarized and liquified in bulk quantities

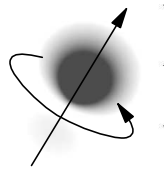
⇑ Spin precession can be detected by a SQUID magnetometer

? Magnetic self-interactions will be a major issue

- Spherical Cell
- Data analysis

? Leakage Currents

Conclusions



- Limits on EDMs of the neutron, electron and ^{199}Hg provide comparable and orthogonal constraints on CP violation beyond the Standard Model.

- Limits on electron and ^{199}Hg EDMs can be expected to be reduced in the near future.

- Although current techniques used to search for EDMs are reaching their limits, new ideas should allow improvements by a factor of 100 to 10^4