Constraints on CP Violation from Searches for Nuclear Electric Dipole Moments

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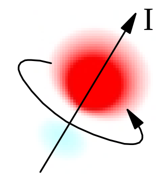

Outline

- T and CP violation by a permanent EDM
- Overview of CP violation
- Overview of EDM Searches
- Search for EDM in ^{199}Hg
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  - ⇒ EDM vapor cells
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- Search for EDM in liquid ^{129}Xe
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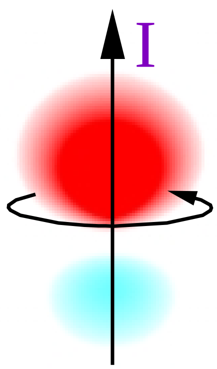
  - ⇒ Low field detection with high-T_c SQUIDs
  - ⇒ Controlled spin dephasing

T and CP violation by a permanent EDM

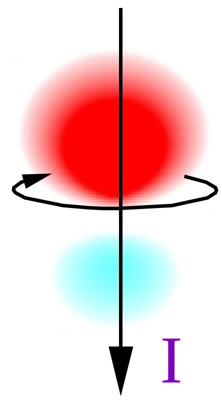
- Time Reversal:



$$t \rightarrow -t$$

$$\vec{I} \rightarrow -\vec{I}$$

$$\vec{d} \rightarrow \vec{d}$$



- Vector:

$$\vec{d} = d\frac{\vec{I}}{I}$$

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

$$d \neq 0 \rightarrow \textit{violation of time reversal symmetry}$$

CPT theorem also implies violation of CP symmetry

EDM $\rightarrow$ T violation $\leftrightarrow$ CP violation

- Interaction with electric and magnetic fields:

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

CP violation - still a mystery!

- Matter - antimatter asymmetry of the Universe cannot be explained by CP violation in the Standard Model
  - *New sources of CP violation are required.*

- Strong CP Problem:

  QCD allows a CP violating term $\mathcal{L} = \theta G\tilde{G}$, which for $\theta \sim 1$ gives an EDM 10^{10} times larger than present limits.

- Supersymmetric CP Problem:

  For natural values of parameters Supersymmetry predicts EDMs 100-1000 times larger than present limits.

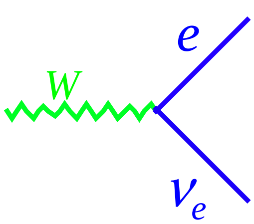
High Energy Approach
CP violation in B mesons

Low Energy Approach
Electric Dipole Moments

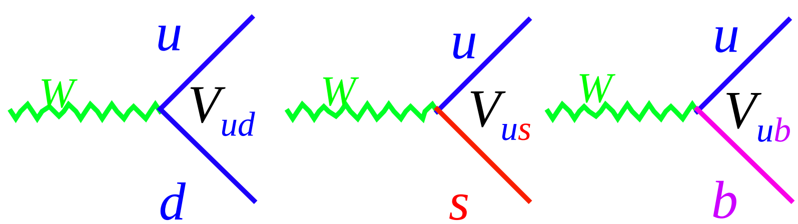
CP violation in the Standard Model

A complex phase in the CKM matrix:

Leptons - no mixing
(massive neutrinos -?)



Quarks
weak eigenstates ≠ mass eigenstates



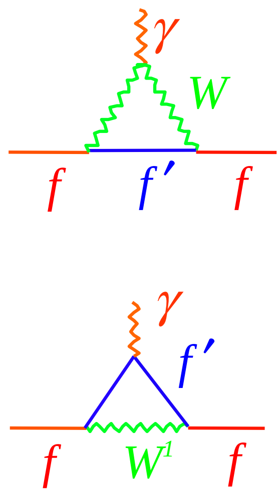
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = R_2 R_1 C R_3$$

$$R_1 = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \ \ldots, \quad C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

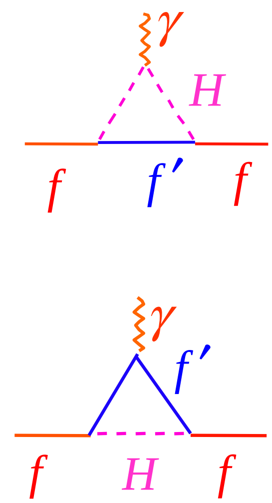
From K^0 mesons : $\delta = -1.2 \pm 0.2$

EDMs are induced by loop diagrams

Boson exchange



Higgs exchange



- For CP violation only in the CKM matrix these and several higher order diagrams cancel!
- Standard Model gives EDMs at least 5 orders of magnitude smaller than present limits

A non-zero EDM is a background-free signal of CP violation beyond SM

CP violation beyond the Standard Model

- Standard Model - 2 phases

  ⇒ $\delta_{CKM} \sim O(1)$

  ⇒ $\theta_{QCD} < O(10^{-10})$

- Supersymmetry - 43 phases

  ⇒ $\theta_{SUSY} < O(10^{-2})$ - $O(10^{-3})$

- Naïve estimate:

$$d \sim \frac{em}{\Lambda^2},$$

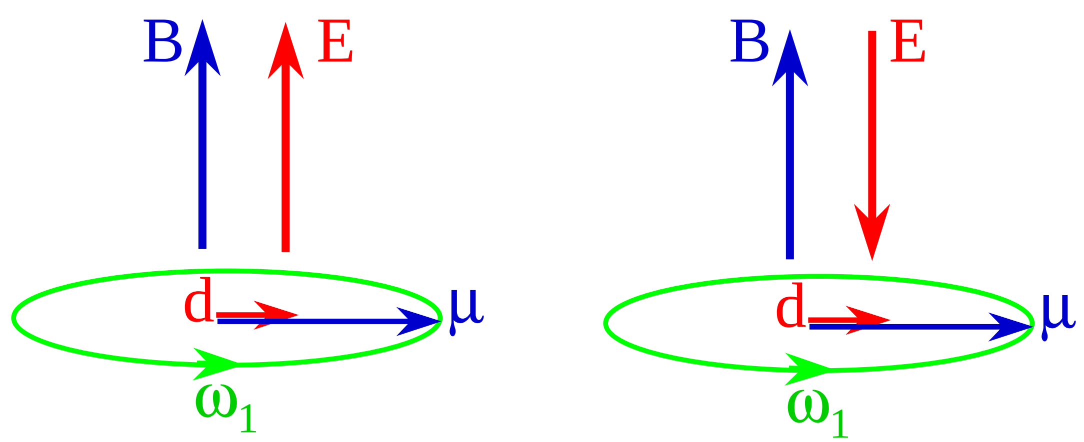
$$10^{-27}\, e\, cm \rightarrow \Lambda = 100 \text{ TeV}$$

- SUSY

$$d_f \simeq -\frac{e\alpha}{24\pi}\frac{m_f A_{\bar{f}}}{M_{\bar{f}}^3}\sin(\varphi_A - \varphi_{\bar{f}})$$

Experimental Detection of an EDM

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



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

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

Statistical Sensitivity

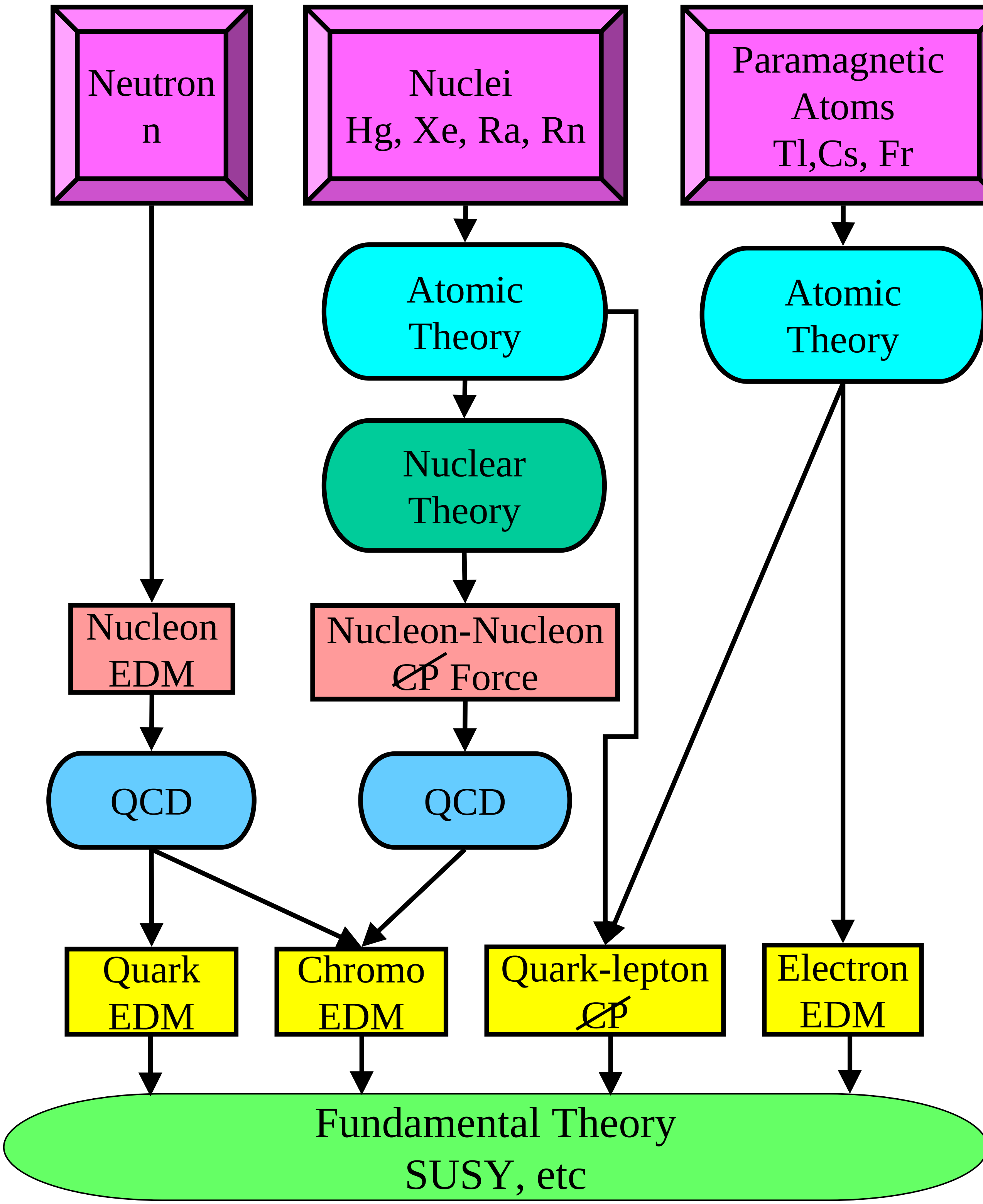
Single atom with coherence time τ:

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

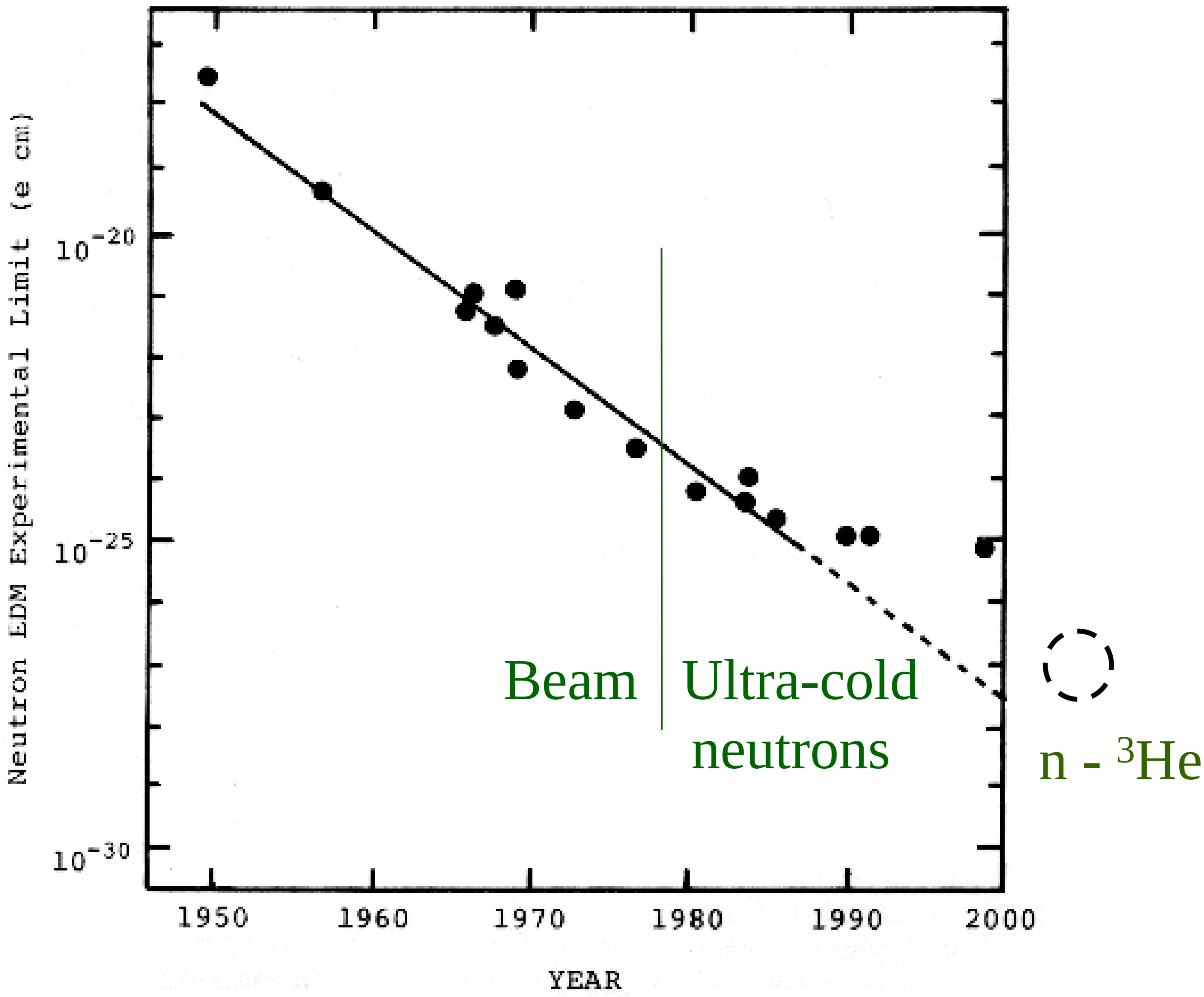
N uncorrelated atoms measured for time $T >> \tau$:

$$\delta d = \frac{\hbar}{2E}\frac{1}{\sqrt{2\tau T N}}$$

3 Types of EDM Searches



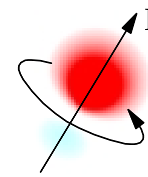
Search for EDM of the neutron

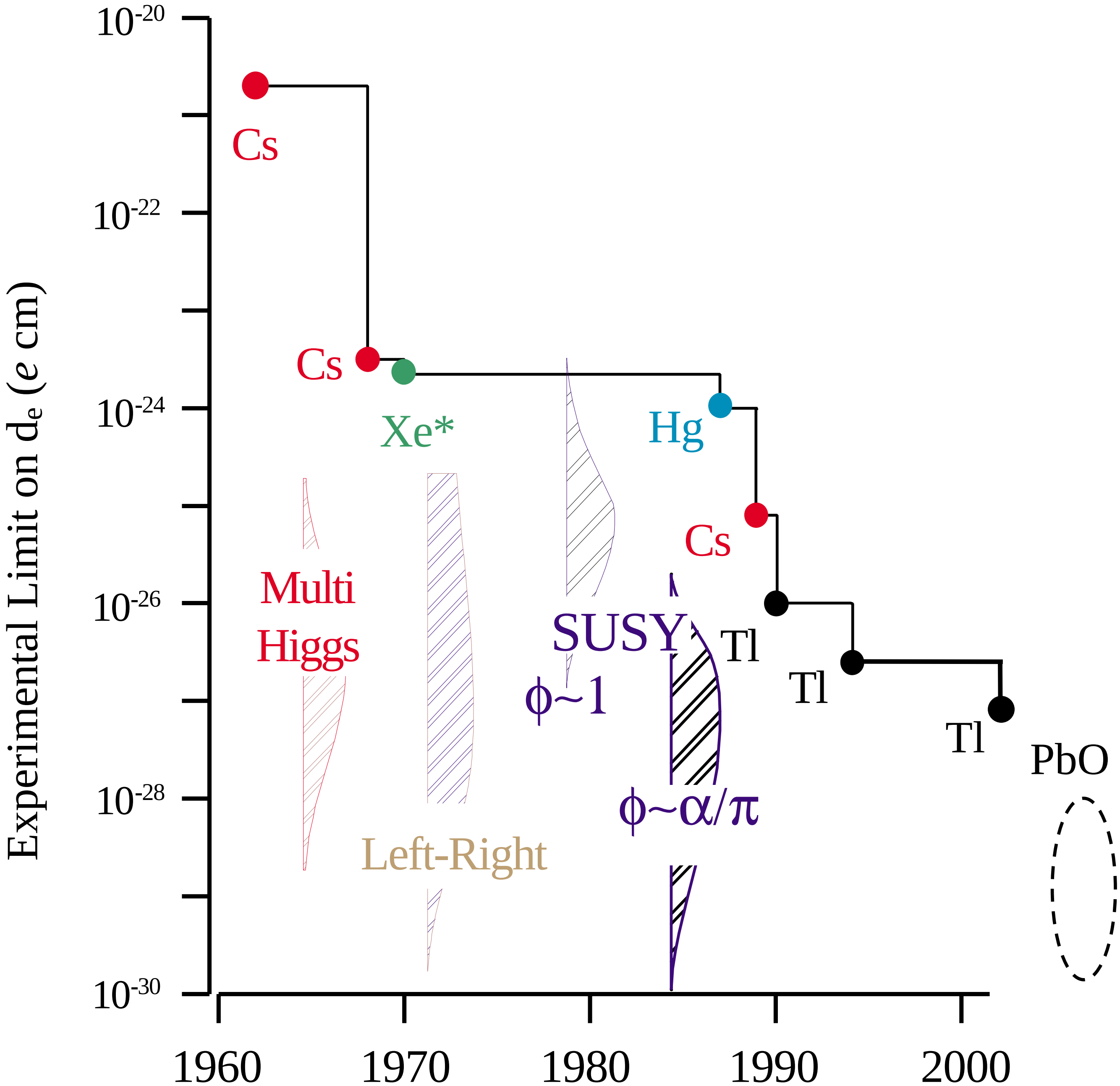


$|d_n| < 6.3 \times 10^{-26}$ e cm (90% C.L.)

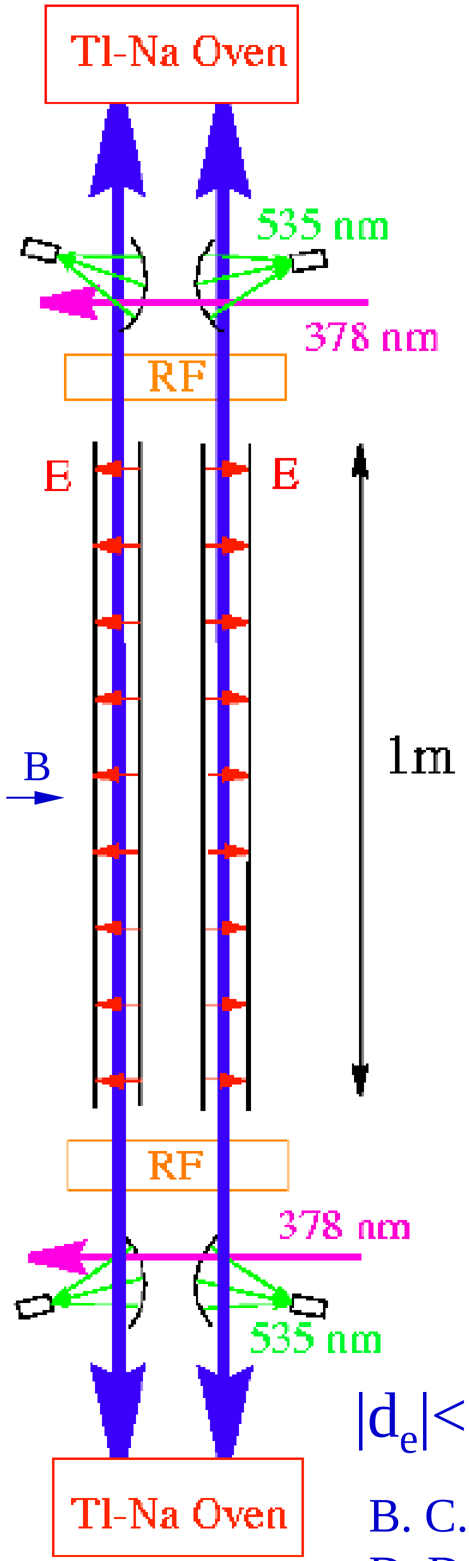
P.G. Harris *et al.*, Phys. Rev. Lett. **82**, 904 (1999)

Search for the Electron EDM





Berkeley Tl Experiment



- Heavy Atom Enhancement

$$d_a \propto d_e \alpha^2 Z^3$$

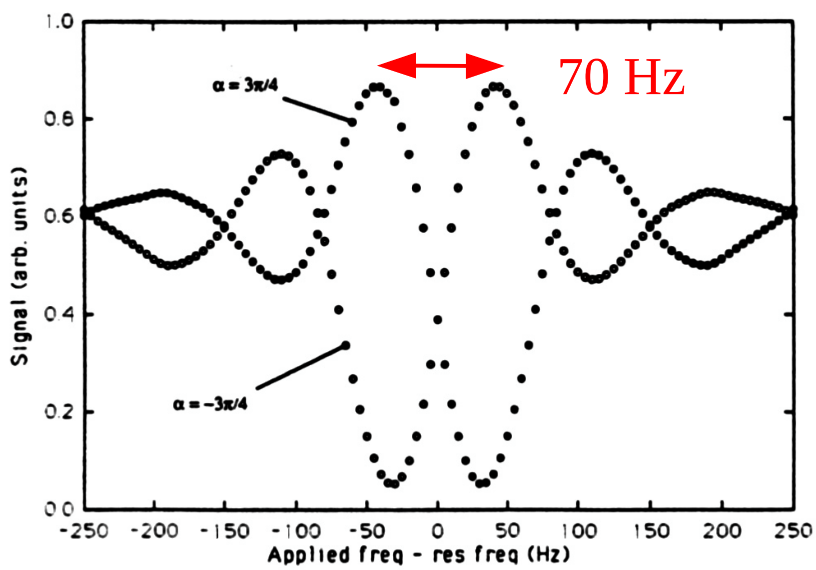
⇒ Spin-orbit interaction

⇒ Nuclear Coulomb field

⇒ Relativistic enhancements

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

Ramsey Fringes

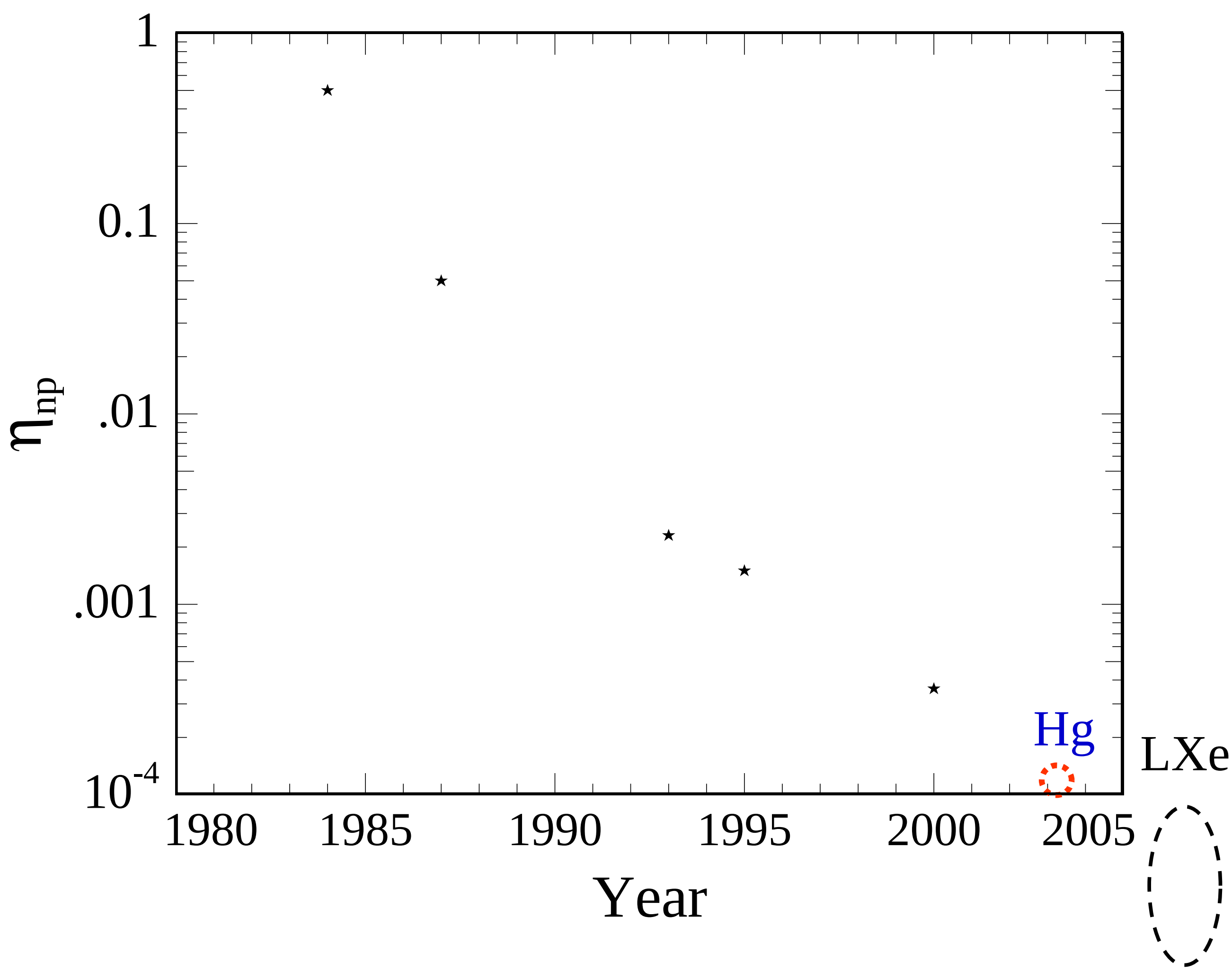


$|d_e| < 1.6 \times 10^{-27}$ e cm (90% C.L.) (2002)

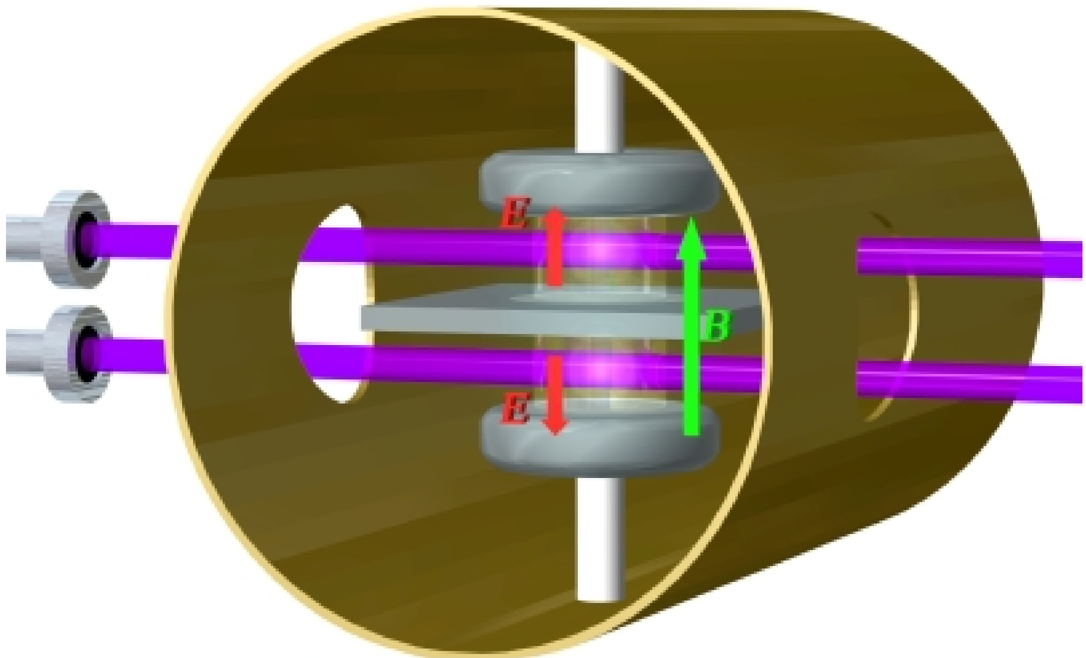
B. C. Regan, E. D. Commins, C. J. Schmidt, and D. DeMille, Phys. Rev. Lett. **88**, 071805 (2002)

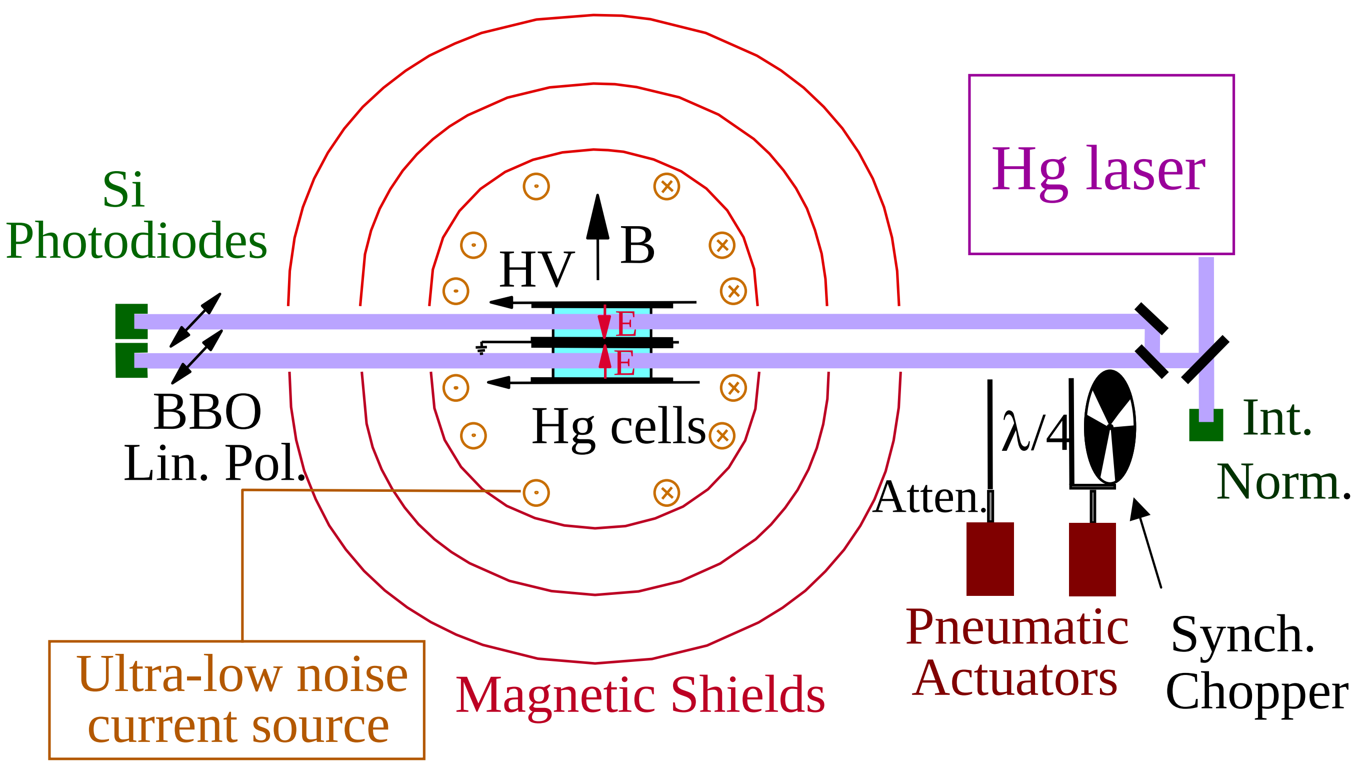
Search for EDM of Diamagnetic Atoms

η_{np} - strength of CP-violating n-p interaction

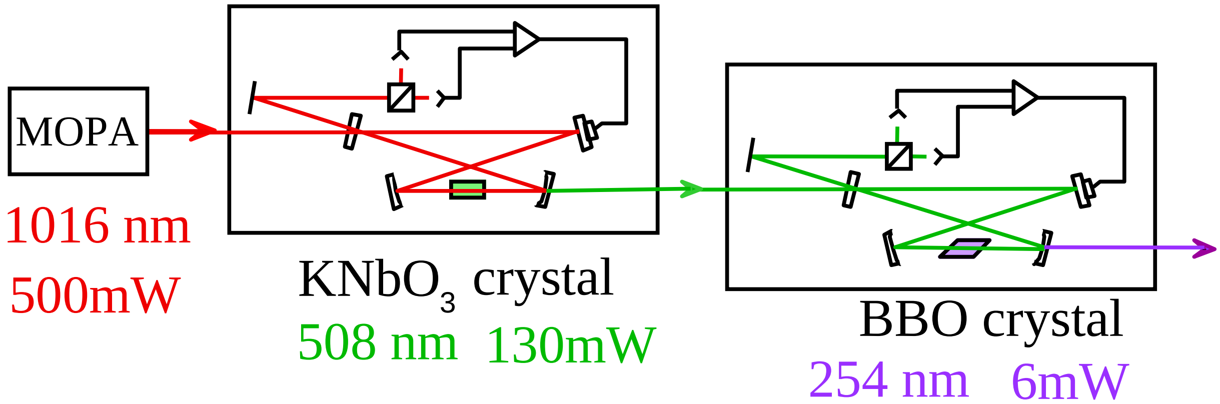


^{199}Hg EDM Experiment



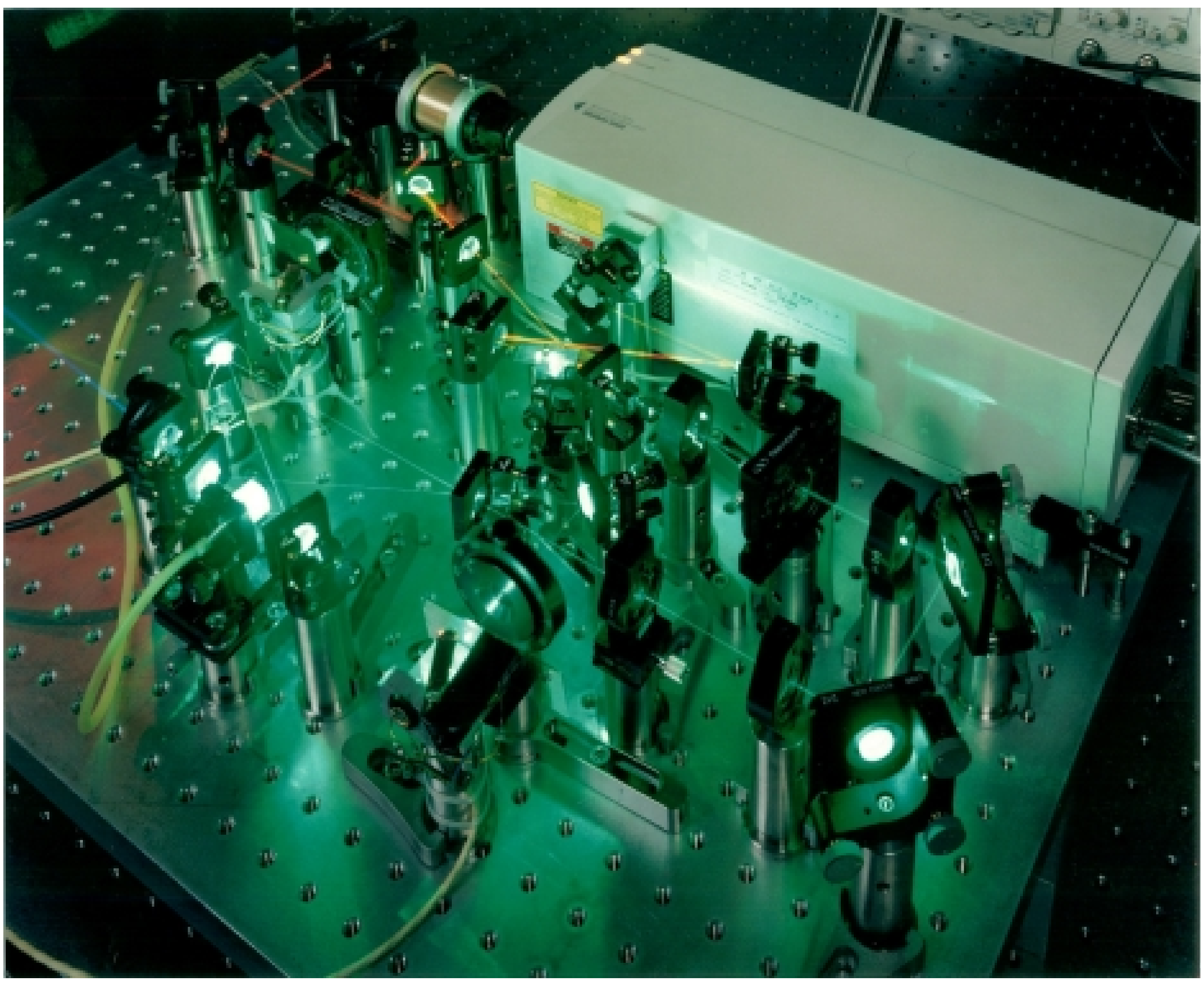


UV laser system at 254 nm for $^1S_0$- $^3P_1$ Hg line

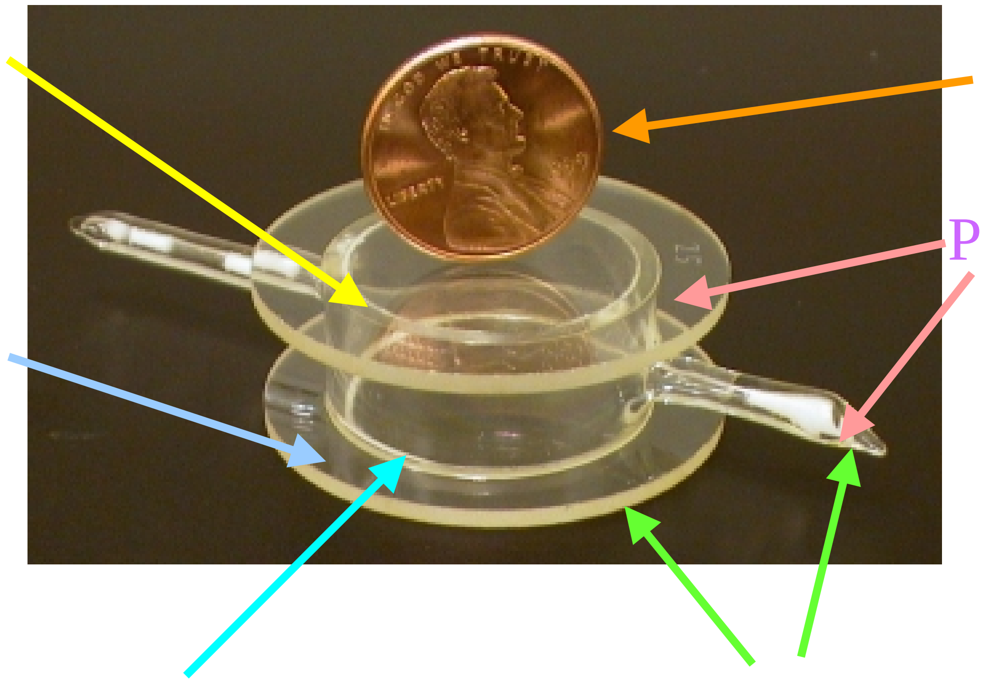


Amplitude noise 10^{-4} rms/√Hz

Over 30,000 hours of operation with no power degradation



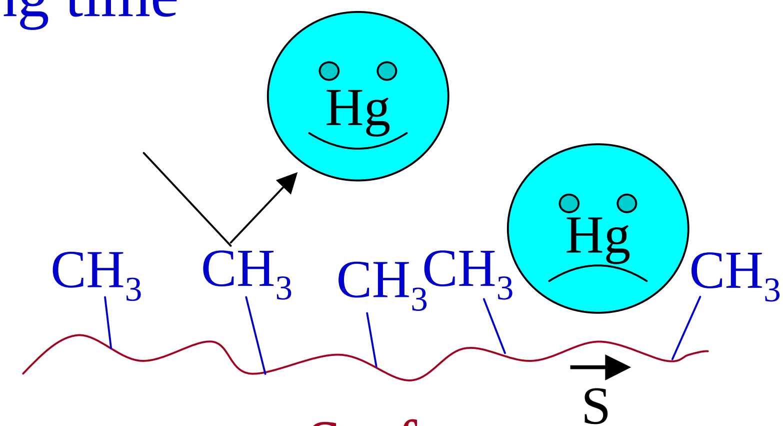
^{199}Hg Cells



Number of ^{199}Hg atoms:	2×10^{14}
Optical depth on resonance:	2.5
Spin relaxation time:	100 – 200 sec
Leakage currents at 10 kV:	0.5 – 1 pA

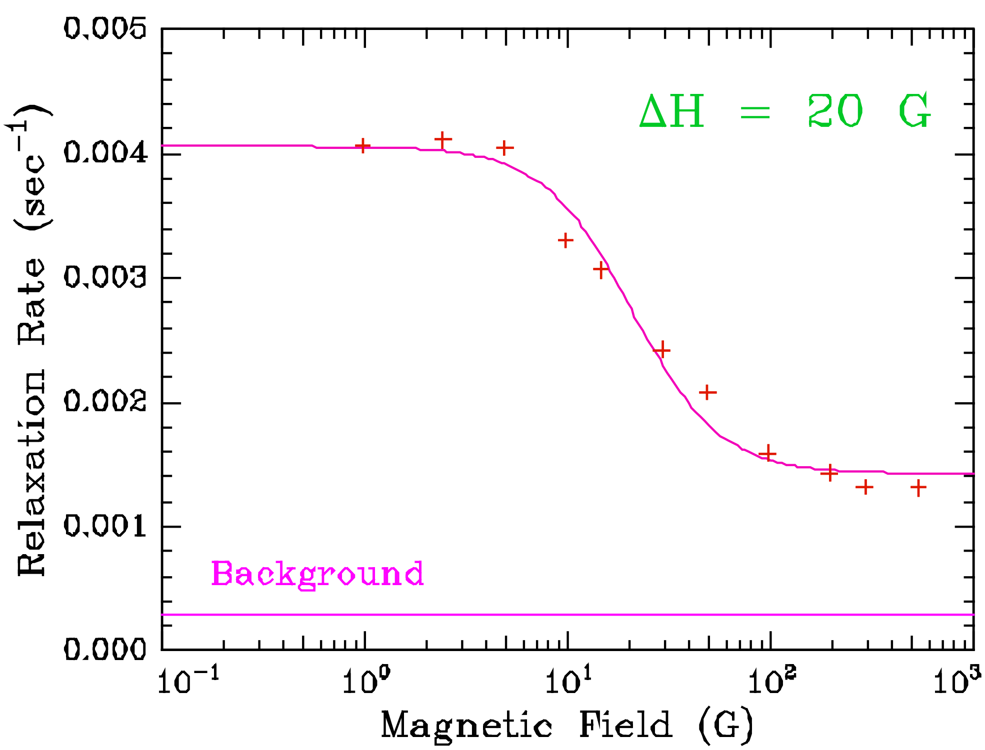
Surface relaxation of ^{199}Hg

- Use hydrocarbon coatings to reduce surface sticking time

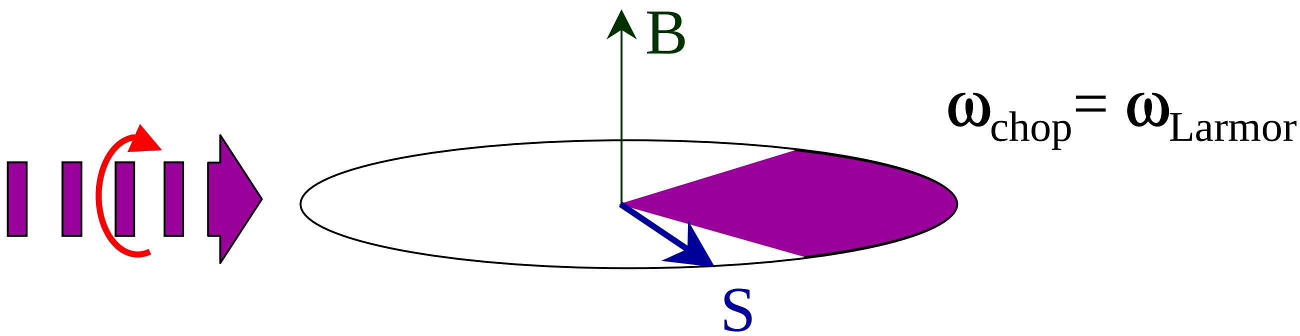


- Relaxation due to paramagnetic sites, some created by UV exposure

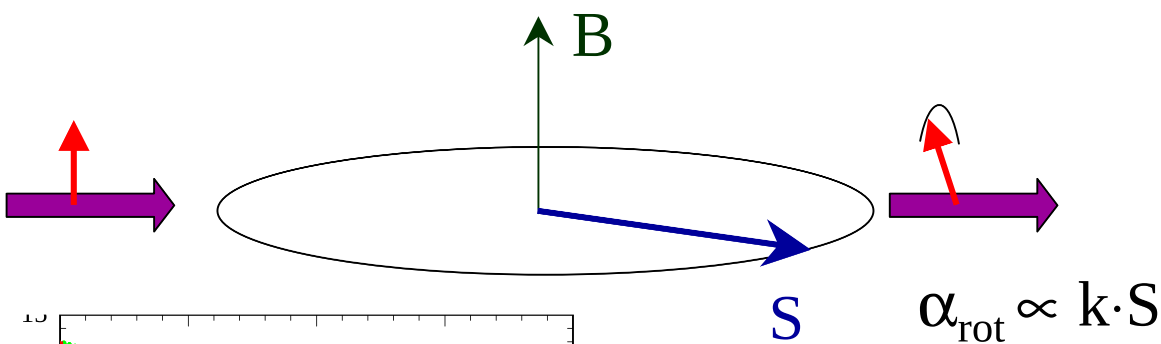
Magnetic Field Dependence

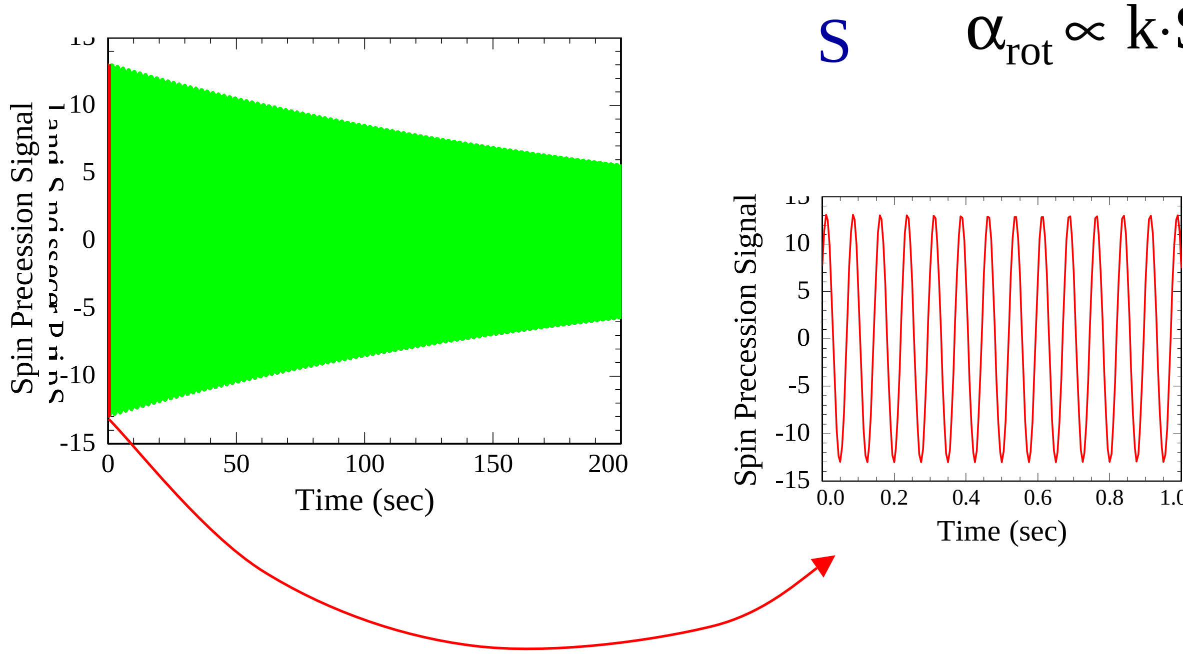


Synchronous Optical Pumping



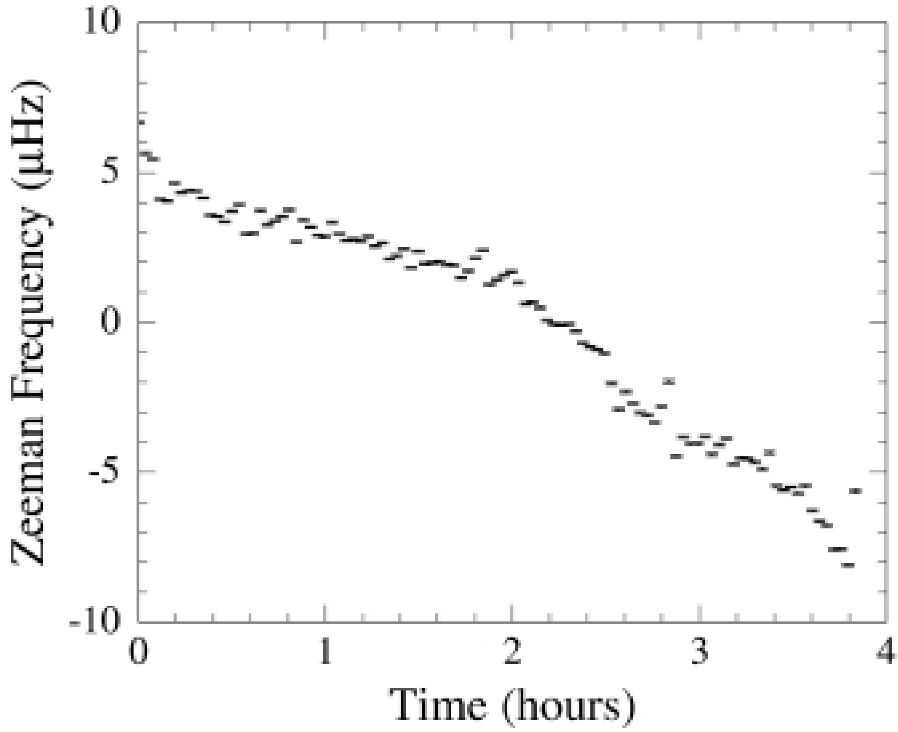
Monitoring Spin Precession





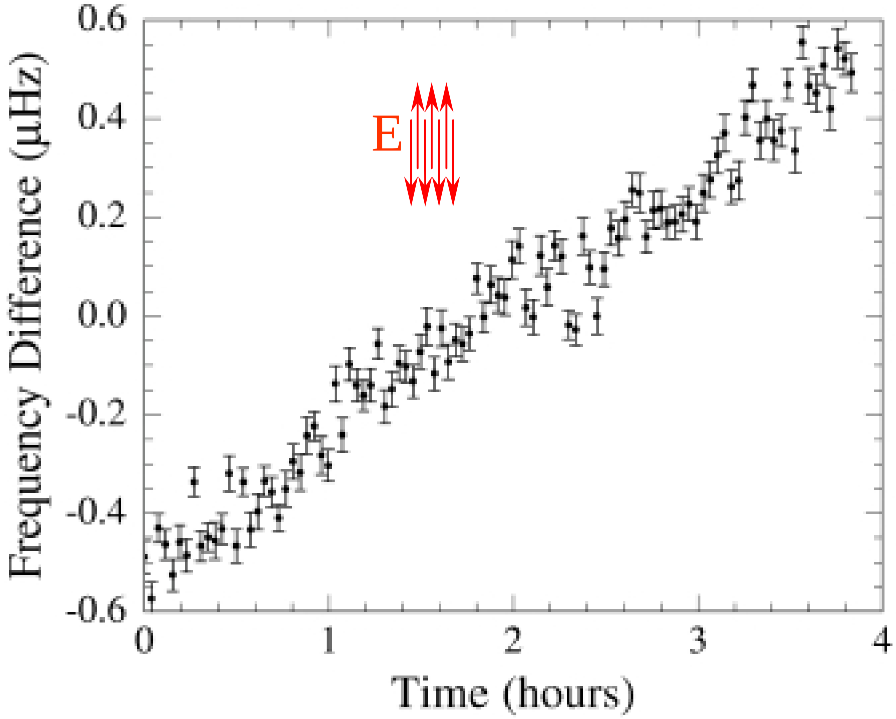
Fit to: $A * \mathrm{Exp}(-t/T_2) * \mathrm{Sin}(\omega t + \phi)$

Frequency Measurements



– Single Cell

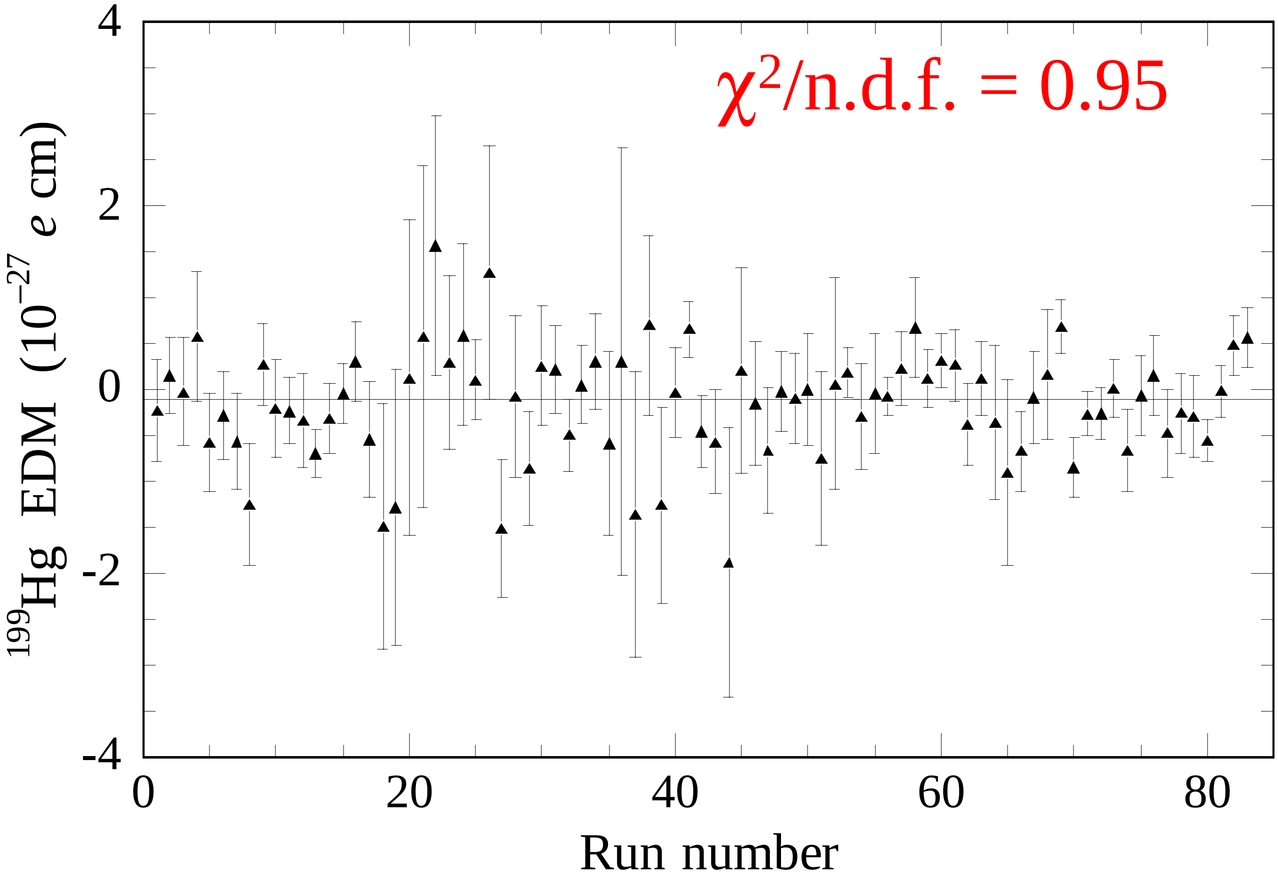
$\delta\omega/\omega = 10^{-9}$



–Frequency Difference

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

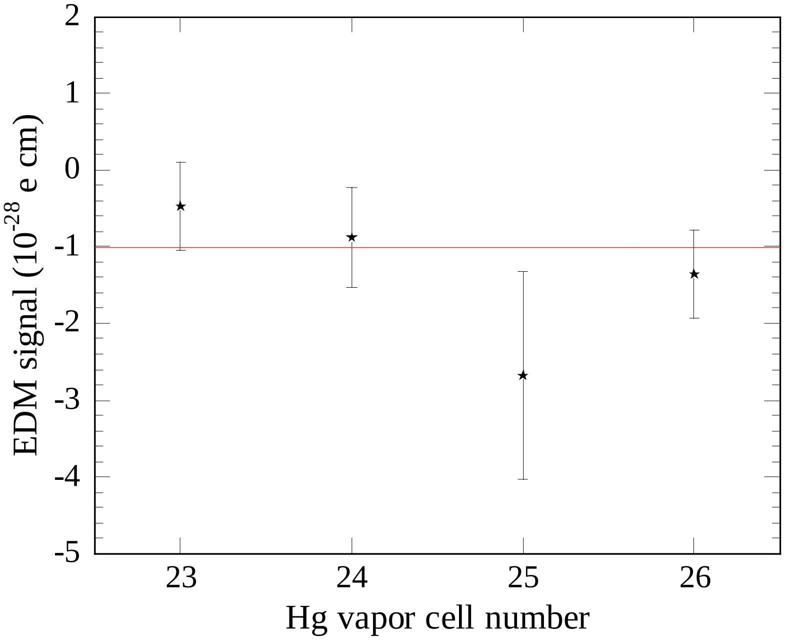
^{199}Hg EDM Data



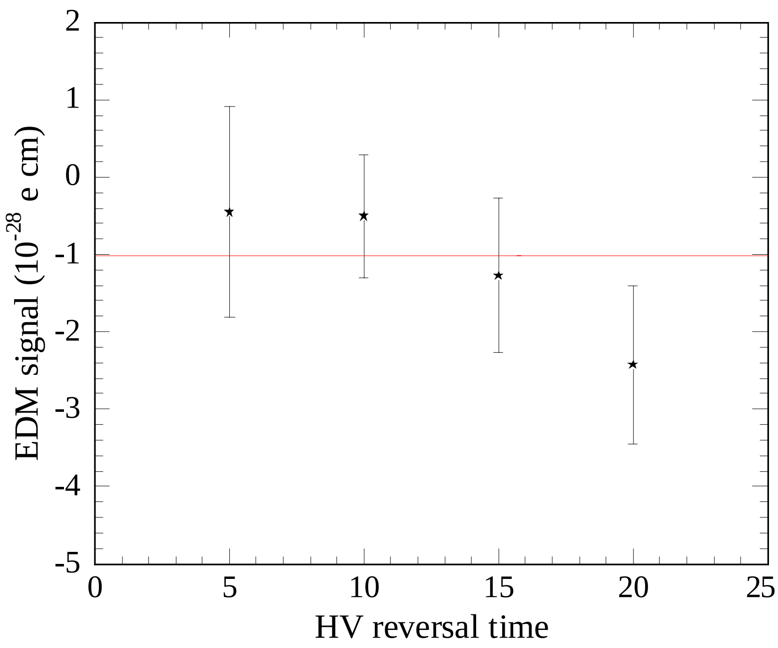
- 50,000 electric field reversals
- Regular reversals of
  - ⇒Magnetic Field
  - ⇒Acquisition Channels
  - ⇒EDM cells
- Other changes in the apparatus

Systematic Effects

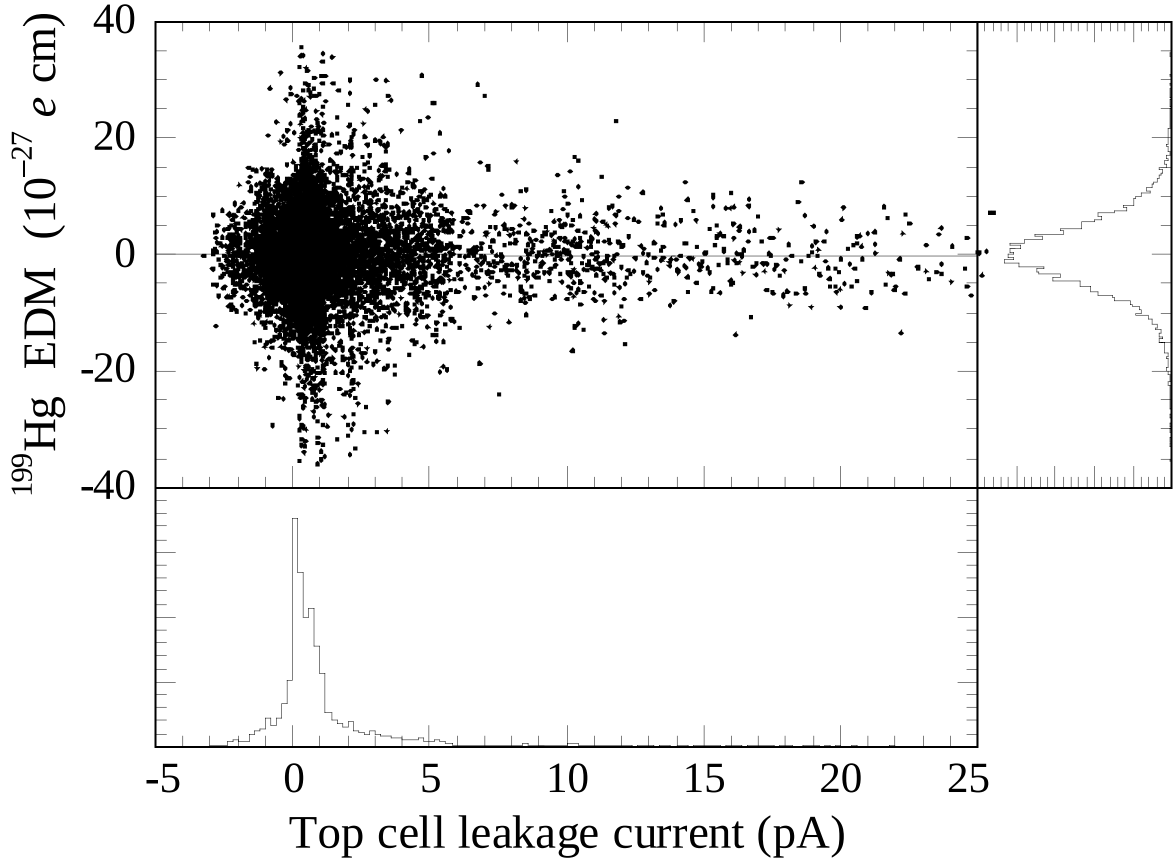
Variation between EDM cells



Dependence on HV reversal time



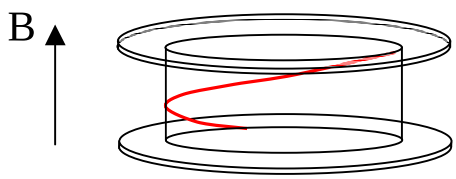
Leakage Currents



Correlation Slope: $[-0.4 \pm 2.0]\times10^{-29}$ *e* cm/pA

From correlation: $d_{\text{leak}} < 0.14\times10^{-28}$ *e* cm

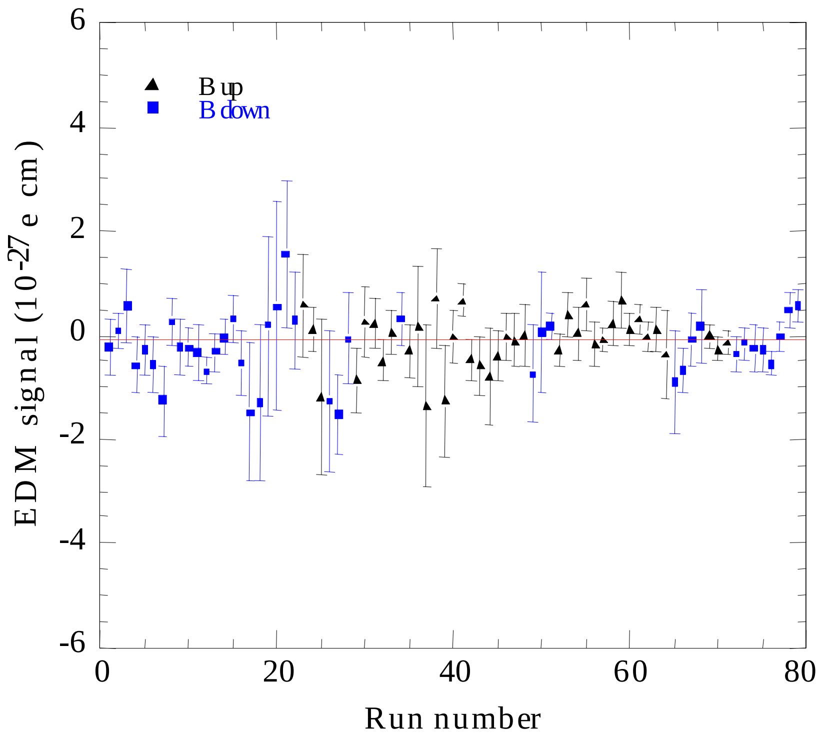
Only helical leakage currents contribute:



One complete loop around the cell with $I = 0.6$ pA:

$d_{\text{leak}} < 0.25\times10^{-28}$ *e* cm

Magnetic Field Reversal

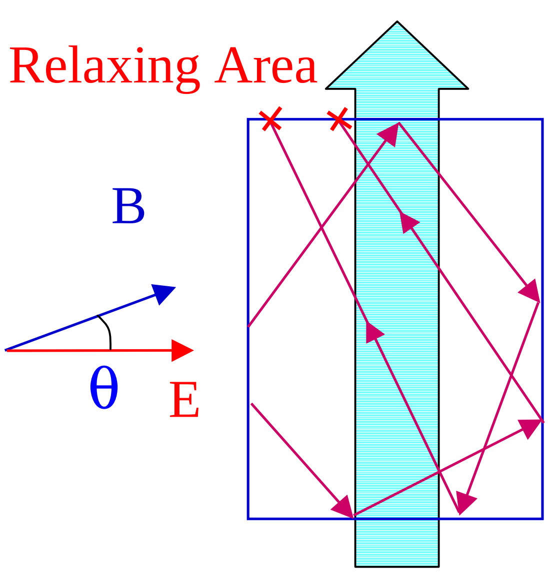


$$d_{up} = -[1.78 \pm 0.70] \times 10^{-28} e \text{ cm}$$

1.4σ

$$d_{down} = -[0.36 \pm 0.69] \times 10^{-28} e \text{ cm}$$

Residual $B_m = v \times E$ magnetic field



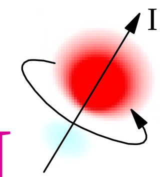
$B_m \propto \sin(\theta)$

Take data with sin(θ) increased by a factor of 5

$$d_B < 0.3 \times 10^{-28} e \text{ cm}$$

Monitoring for correlation with the electric field of 30 parameters

Parameter	Correlation with electric field	Statistical significance
Time between runs (msec)	8.31	1.3
Cell 1 Frequency (nHz)	2.49	0.6
Cell 1 Frequency Error (nHz)	0.02	0.5
Cell 2 Frequency (nHz)	1.52	0.4
Cell 2 Frequency Error (nHz)	-0.02	-0.6
Cell 1 Relaxation Time (msec)	0.28	0.6
Cell 2 Relaxation Time (msec)	0.72	1.2
Cell 1 Initial Phase (mrad)	22.19	1.4
Cell 2 Initial Phase (mrad)	15.65	1.0
Cell 1 Rotation Amplitude (μrad)	-1.17	-1.4
Cell 2 Rotation Amplitude (μrad)	-0.91	-0.9
Cell 1 Transmission (μV)	1.95	0.1
Cell 2 Transmission (μV)	-1.42	0.0
Outside Field B_x (nG)	-9.11	-0.2
Outside Field B_y (nG)	0.87	1.2
Outside Field B_z (nG)	-25.30	-1.5
Cavity 1 Piezo Postion (kHz)	-2.15	-0.2
Cavity 1 Piezo Postion (kHz)	-8.92	-0.9
Laser Power (μV)	0.22	0.5
Laser Current (μV)	-0.52	-1.0
Temperature (μK)	-0.60	-1.4
Horizontal Laser Beam Position (nm)	-0.28	-1.0
Vertical Laser Beam Position (nm)	-0.03	-0.1
Beam Transmission (μV)	0.34	0.2
Cell 1 Background Drfit (nrad)	0.41	0.0
Cell 2 Background Drfit (nrad)	6.19	0.5
Cell 1 Amplitude Deviations ($x10^{-6}$)	1.26	1.3
Cell 2 Amplitude Deviations ($x10^{-6}$)	-0.16	-0.2
Cell 1 Phase Deviations (μrad)	-0.04	-0.4
Cell 2 Phase Deviations (μrad)	0.10	1.1
Initial Phase Difference (μrad)	-6.20	-0.3



New Limit on ^{199}Hg EDM

$d_{Hg} = -[1.06 \pm 0.49 \pm 0.40] \times 10^{-28}$ e cm

$d_{Hg} = -[1.01 \pm 0.63] \times 10^{-28}$ e cm

$|d_{Hg}| < 2.1 \times 10^{-28}$ e cm at 95% C.L.

Previous limit [1]:

$d_{Hg} = -[1 \pm 2.4 \pm 3.6] \times 10^{-28}$ e cm

$|d_{Hg}| < 8.7 \times 10^{-28}$ e cm 95% C.L.

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

Interpretation of ^{199}Hg EDM Limit

- No atomic EDM due to EDM of the nucleus
  – Schiff's Theorem

  ⇒Electrons screen electric field

- d(Hg) is due to nuclear Schiff moment S –
  Difference between mean square radius of the charge distribution and electric dipole moment distribution

$$\vec{S} = \frac{2\pi}{5}\int dx^3 \rho(x)\left(x^2\vec{x} - \frac{5}{3}\langle r^2\rangle_{ch}\vec{x}\right)$$

  ⇒Schiff moment induces parity mixing of atomic states, giving an atomic EDM:

$$d_a = R_A\, S$$

  ⇒R_A - from atomic wavefunction calculations, uncertainty 30%

- The Schiff moment is induced by $\not{CP}$ nucleon-nucleon interaction:

$$\xi_{np}\frac{G_F}{\sqrt{2}}(\bar{p}p)(ni\gamma_5 n)$$

  ⇒Due to coherent interactions between the valence nucleon and the core

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

  ⇒R_N - Calculated only in the simplest shell model

  ⇒Large uncertainty due to collective excitations

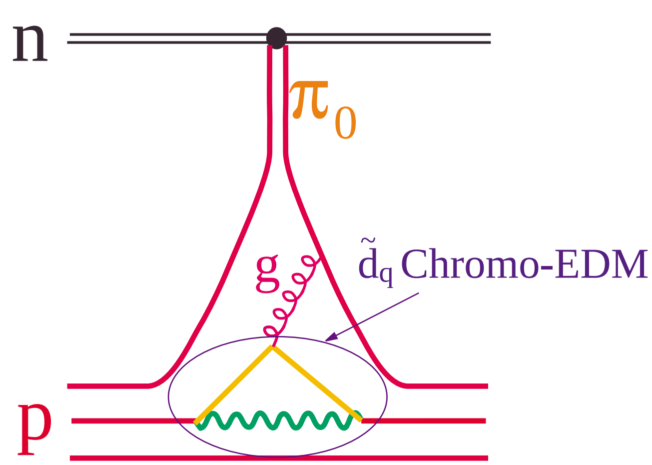
Interpretation of ^{199}Hg EDM Limit (Continued)

- $\not{CP}$ nucleon-nucleon interaction is proportional to CP-odd nucleon-pion constant $\bar{g}_{\pi NN}$

$$\xi = \frac{g_{\pi NN}\,\bar{g}_{\pi NN}\sqrt{2}}{G m_\pi^2}$$

$\Rightarrow$New limit on $|\bar{\theta}| < 1.5\times10^{-10}$

- Can be induced by chromo-electric dipole moments of the quarks



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

T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999).

Summary of Experimental Limits on Fundamental EDMs

- ^{199}Hg Atom EDM:

$$e\left|\tilde{d}_d - \tilde{d}_u - 0.012\,\tilde{d}_s\right| < 6\times10^{-27}\,e\ \text{cm}$$

- Neutron EDM [1]:

$$\left|e(\tilde{d}_d+0.5\tilde{d}_u)+1.3d_d-0.32d_u\right|<1.1\times10^{-25}\,e\ \text{cm}$$

- Electron EDM:

$$|d_e| < 2.7\times10^{-26}\frac{m_e}{m_d}\text{e cm}$$

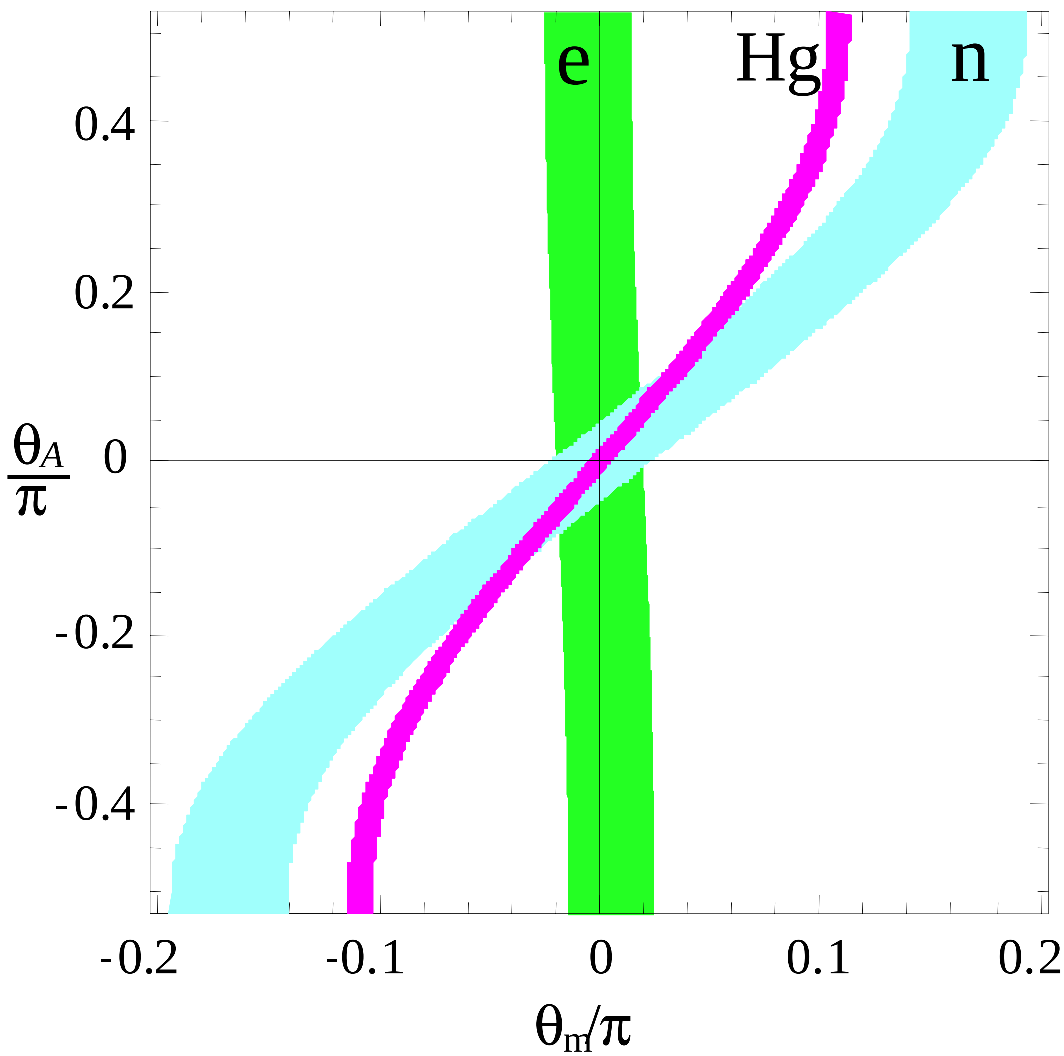
[1]: Pospelov and Ritz, Phys.Rev. D63 (2001) 073015

Limits on Complex phases in Supersymmetry

- Simplified SUSY [1]

  ⇒All masses scales = M, tanβ = 2 [1]

M = 750 GeV

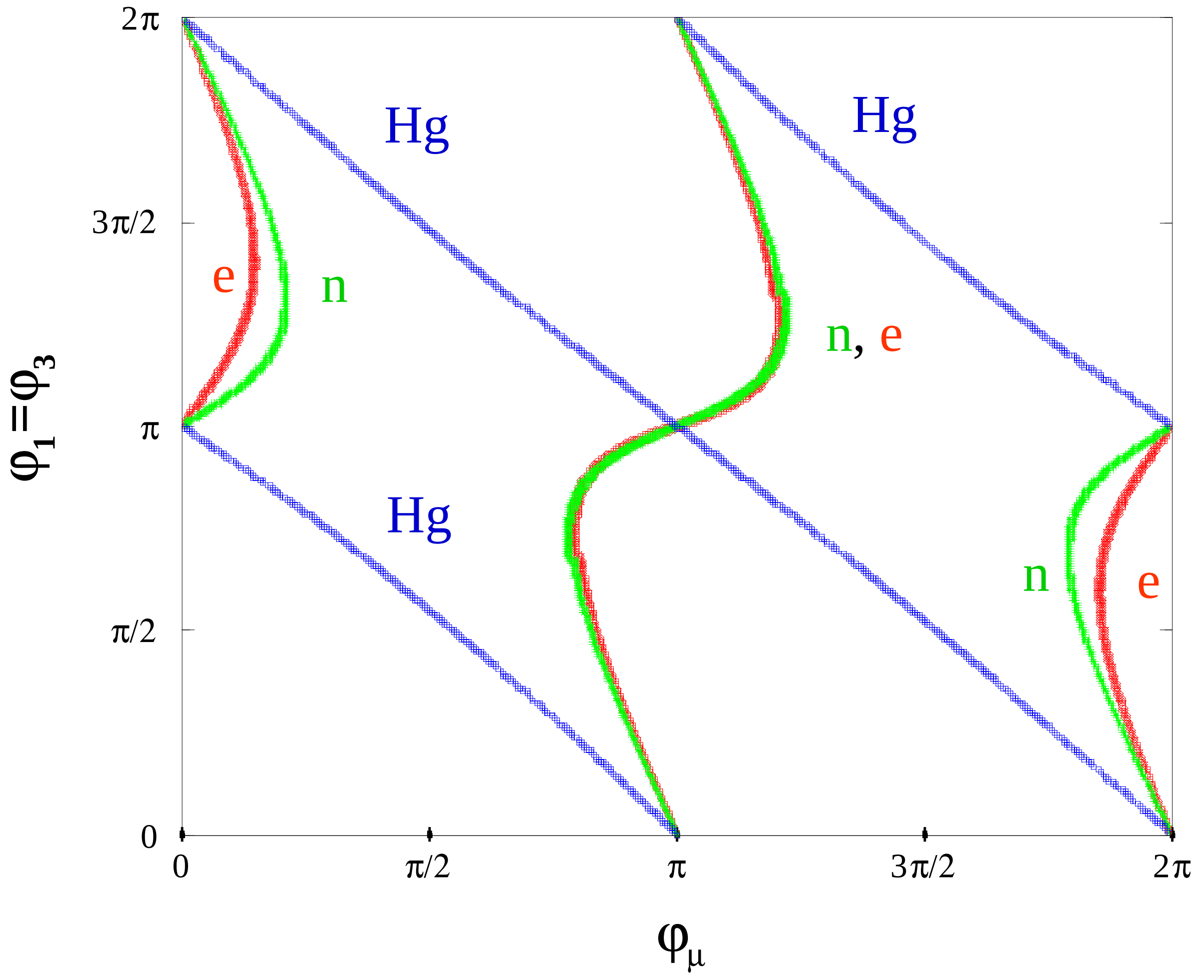


[1] T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999).
M. Pospelov, Private communication

mSUGRA Supersymmetric Models

⇒ $\tan\beta = 2$, $m_{3/2} = 150$ GeV [1]

⇒ Elimination of Cancellation Scenarios [2]



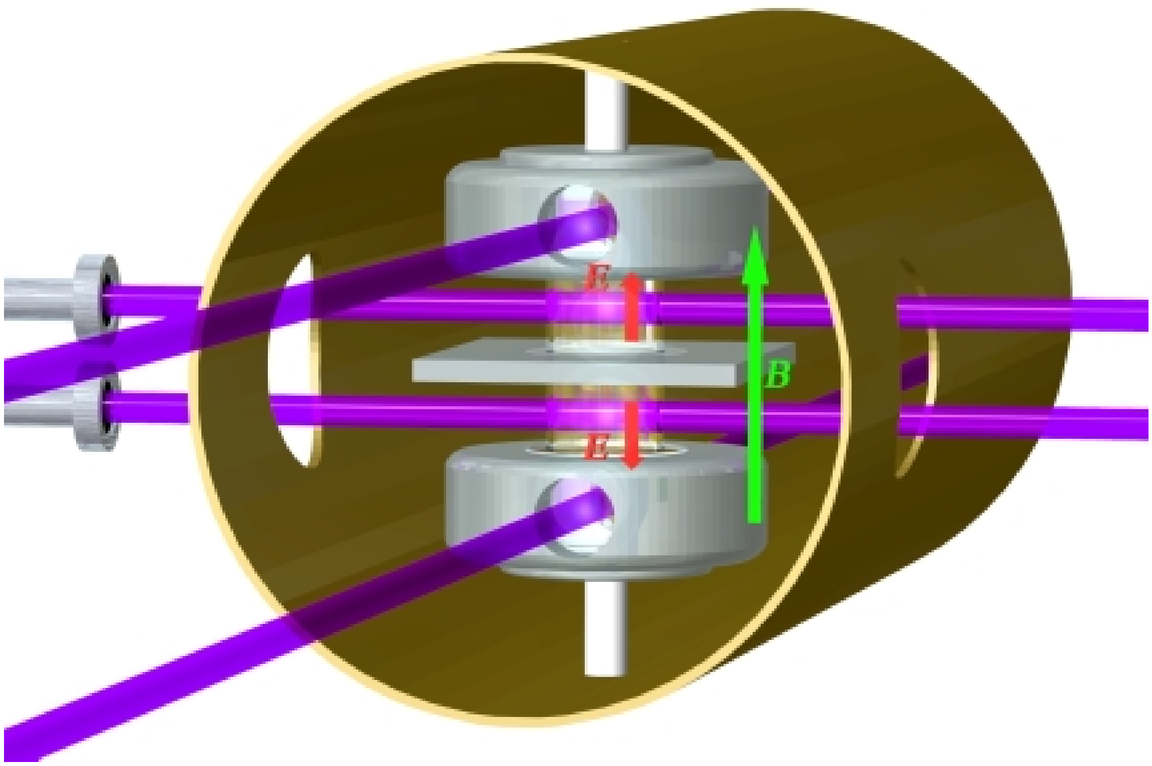
[1] S. Abel , S. Khalil, and O. Lebedev, Nucl.Phys. B606, 151 (2001)
[2] M. Brhlik,L. Everett, G.L.Kane and J. Lykken, Phys. Rev. Lett. 83, 2124 (1999);

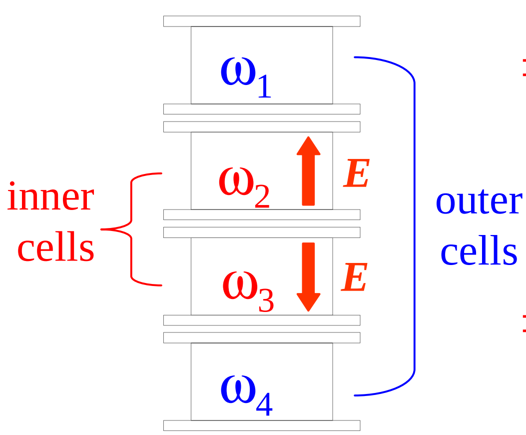
Limits on CP violating parameters

CP violating parameter	Limit from ^{199}Hg	Best limit from other experiments	
QCD Phase θ	$\theta < 1.5\times10^{-10}$	$\theta < 6\times10^{-10}$	n
Supersymmetry Quark ε_q^{susy} Electron ε_e^{susy}	$\varepsilon_q^{susy} < 2\times10^{-3}$ $\varepsilon_q^{susy} < 1\times10^{-1}$	$\varepsilon_q^{susy} < 1\times10^{-2}$ $\varepsilon_e^{susy} < 4\times10^{-2}$	n e
Multi-Higgs ε^{Higgs}	$\varepsilon^{Higgs} < 0.4/\tan\beta$	$\varepsilon^{Higgs} < 0.7/\tan\beta$	e
Left-Right x_q	$x_q < 1\times10^{-3}$	$x_q < 1\times10^{-2}$	n

Further Improvements in ^{199}Hg Experiment

- Use 4 ^{199}Hg cells instead of 2 to reduce magnetic field noise and have better systematic checks





⇒ Magnetic Gradient Noise Cancellation

$$S = (\omega_2 - \omega_3) - 1/3\,(\omega_1 - \omega_4)$$

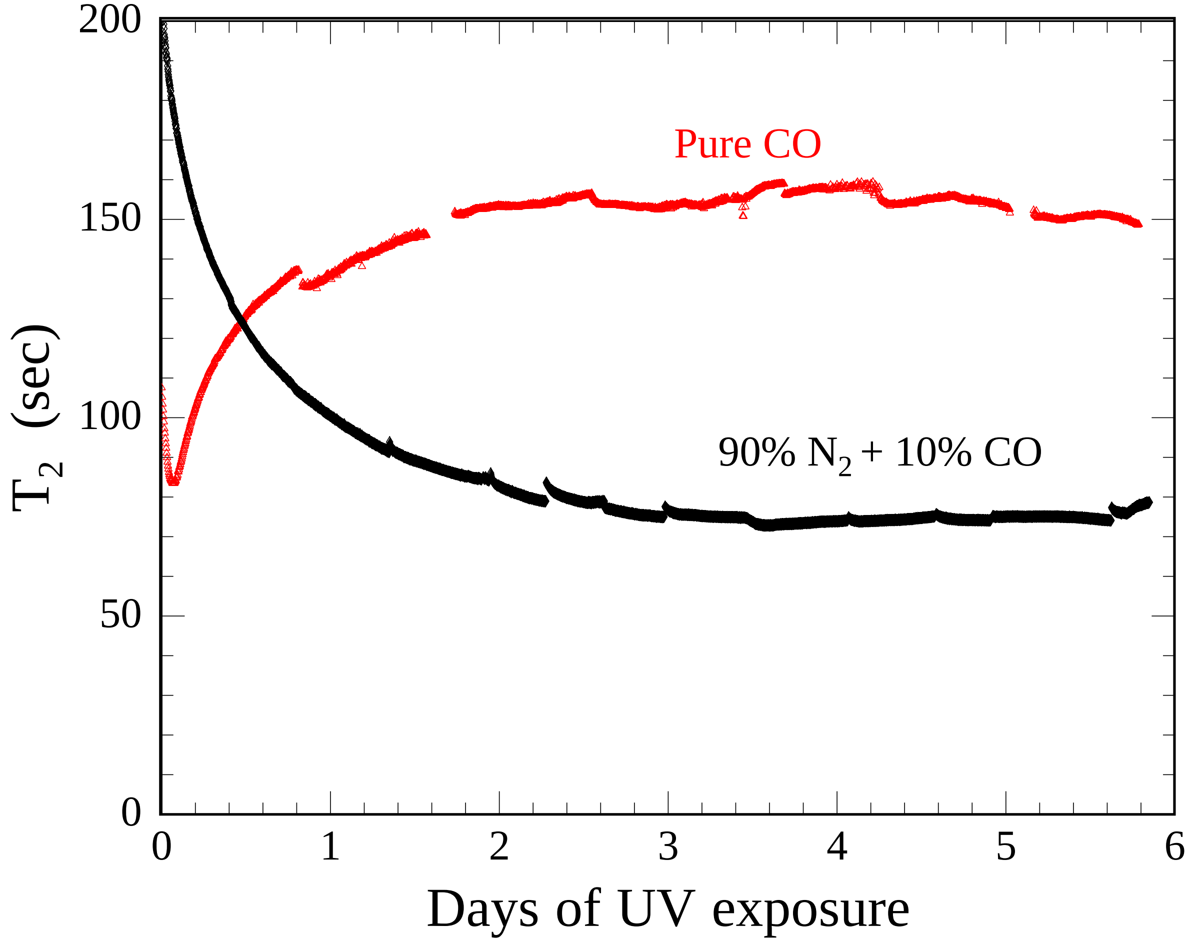
⇒ Leakage Current Diagnostic

$$L = (\omega_2 + \omega_3) - (\omega_1 + \omega_4)$$

Vapor Cell Buffer Gas Composition

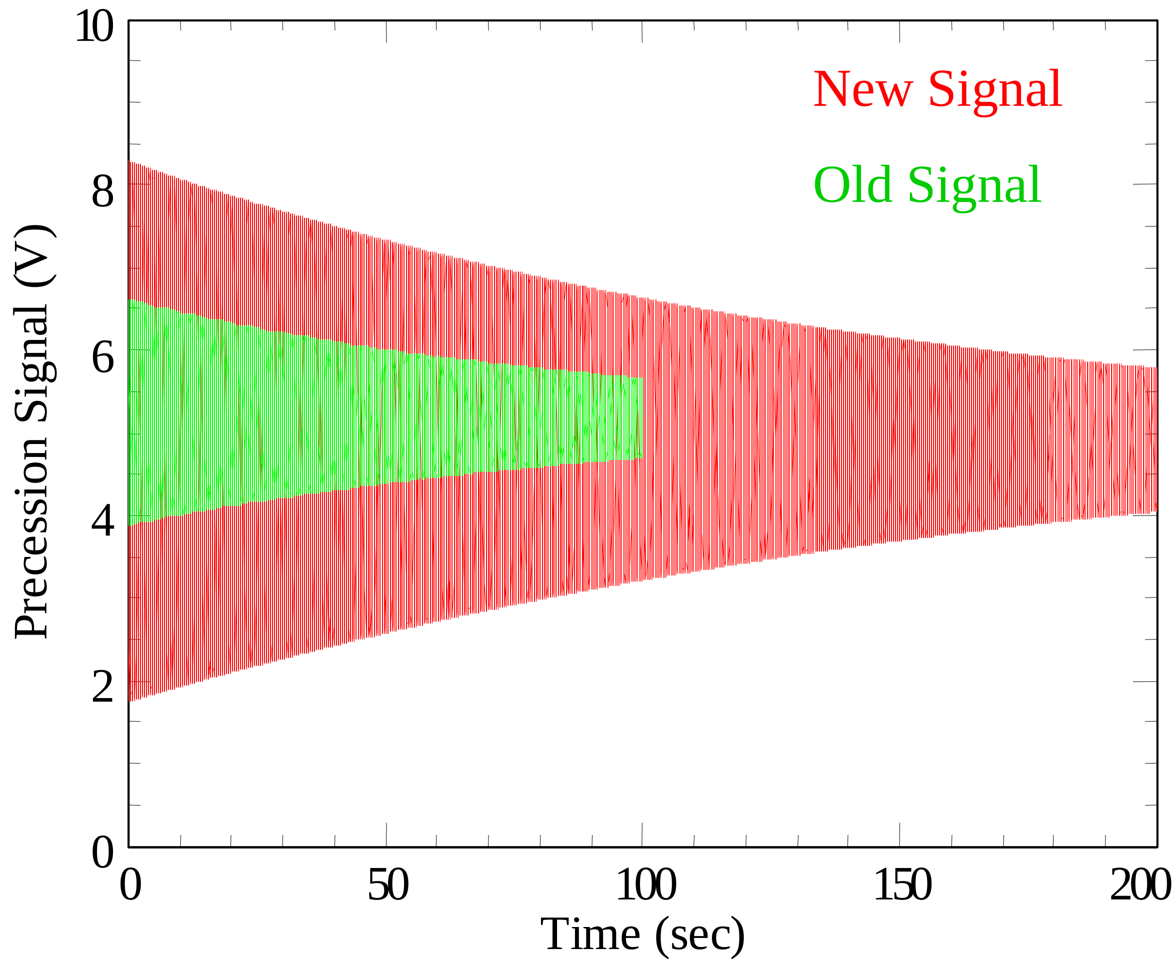
- Previously used 90% N_2 , 10% CO
  - ⇒ N_2 quenches Hg atoms to the metastable ${}^3P_0$ state,
  - ⇒ Metastable Hg atoms diffuse to the wall and cause damage
- Switched to pure CO
  - CO is effective in quenching Hg atoms to the ground state.

Effect of UV on coherence time



New ^{199}Hg Data

- Much better signals
  - ⇒ Better cancellation of 1/f noise
  - ⇒ Larger probe beam intensities
  - ⇒ Longer measurement period



Sensitivity improved by a factor of 3

Search for EDM using liquid ^{129}Xe

$$\delta d = \frac{\hbar}{2E}\frac{1}{\sqrt{2\tau TN}}$$

Relative to ^{199}Hg Experiment

- + Density 10^{22} cm^{-3} — $\uparrow 10^8$
- + Spin lifetime over 1000 sec — $\uparrow 10$
- + Electric field breakdown 400 kV/cm — $\uparrow 50$

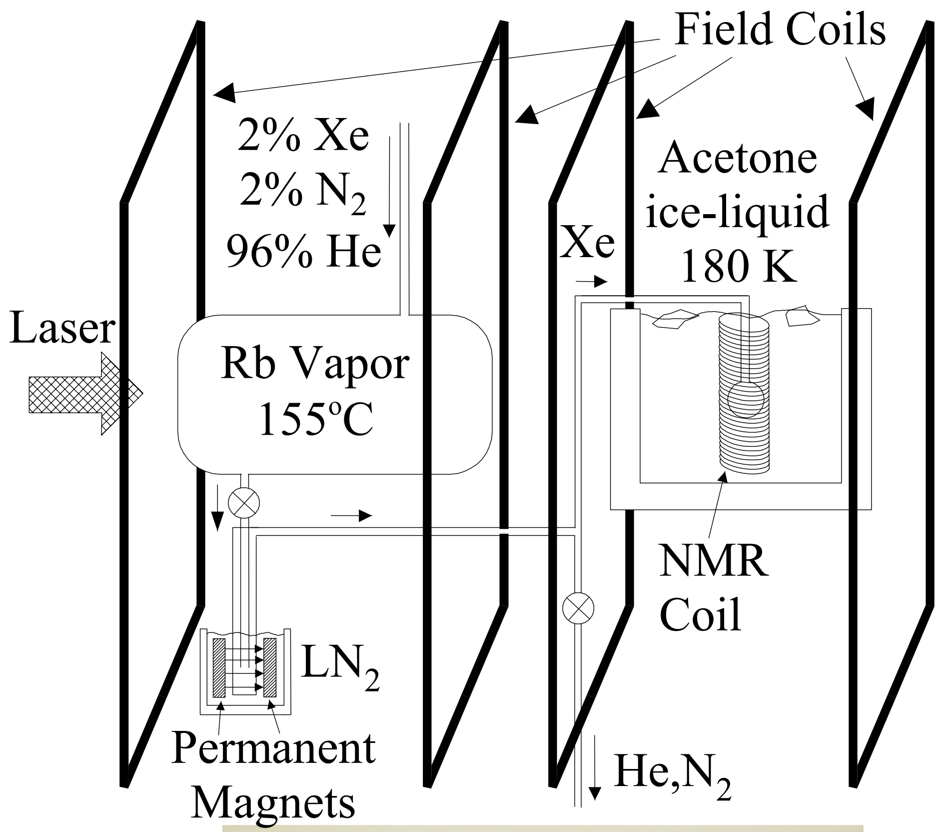
$$\Downarrow$$

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

- + SQUIDs can be used for detection and as a near-magnetometer

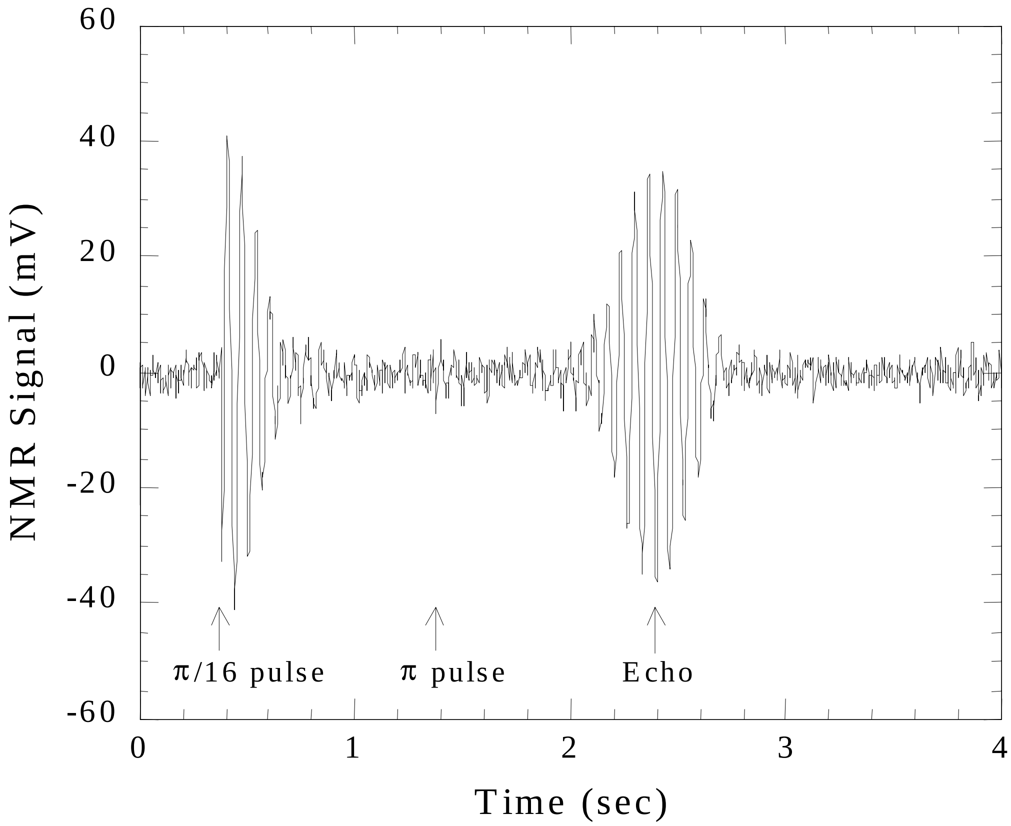
- – Smaller sensitivity to CP interactions by a factor of 10 compared with Hg.

Production of Polarized Liquid Xe



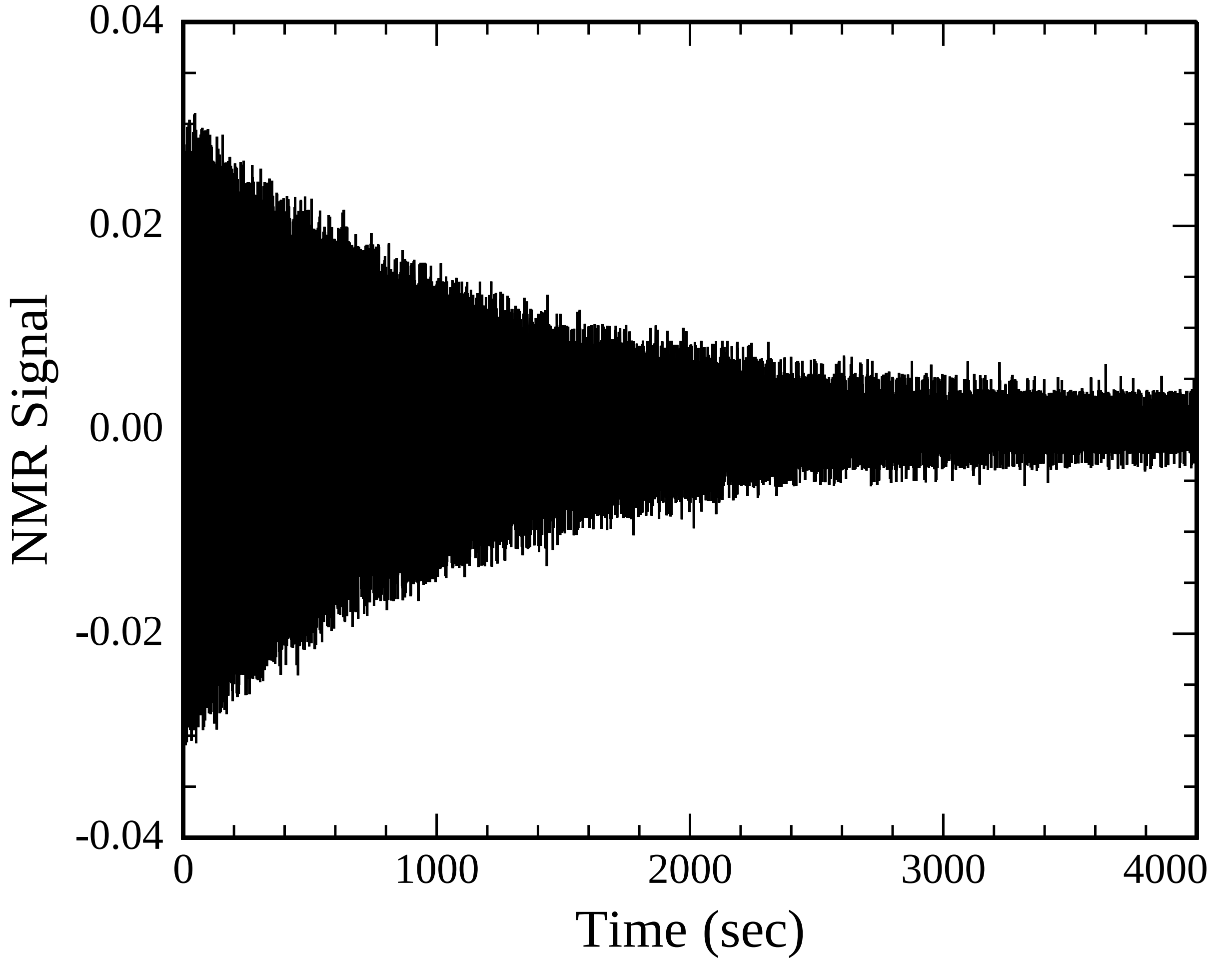
Measurement of the transverse spin relaxation time of liquid ^{129}Xe

- Expect very long $T_2 \sim T_1 = 1800$ sec
- In previous measurements T_2 was limited to ~ 1 sec by technical problems.
- Use spin-echo technique to eliminate dephasing due to external field gradients



Measurement of T_2

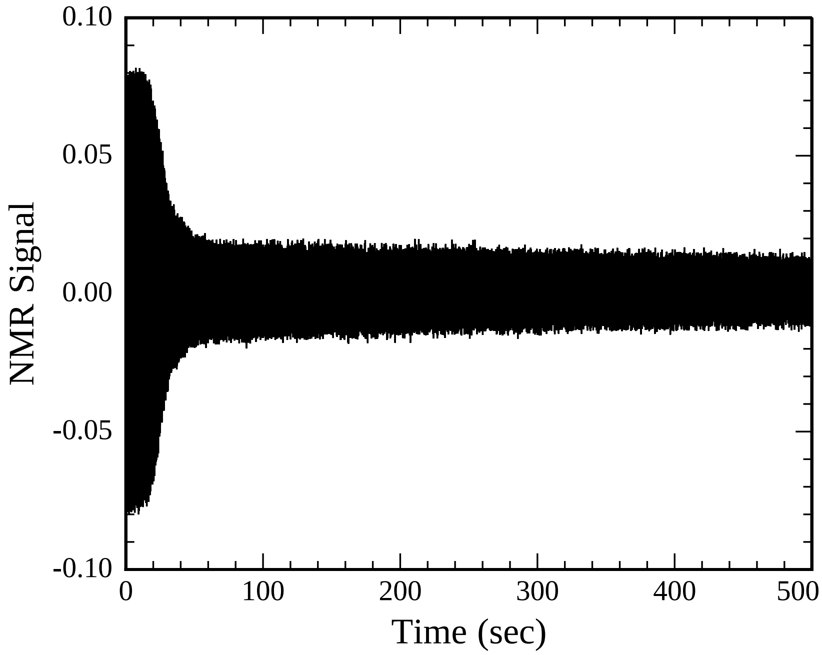
- Use CPMG pulse sequence
  - ⇒π pulses are applied along the axis of the rotating spin magnetization to cancel pulse imperfections
  - ⇒60,000 π pulses



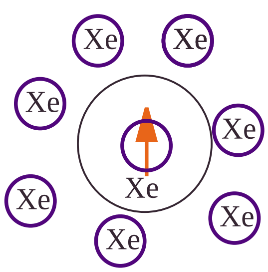
T_2 = 1300 sec

longest ever measured in a liquid

Magnetic dipolar field self-interactions



- In a spherical cell for a uniform magnetic field and magnetization



$$B = \frac{3n(n \cdot m) - m}{r^3} + \cancel{\frac{8\pi}{3} m\delta(r)}$$

$$B_{Xe} = 0$$

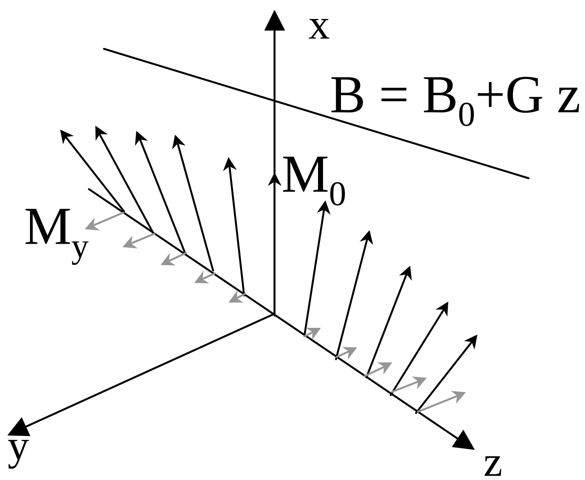
- Magnetization gradients affect precession of ^{129}Xe

- Response to magnetic field gradients is non-linear

- Diffusion has a negligible effect

Response to a linear magnetic field gradient

Rotating Frame



Linear response

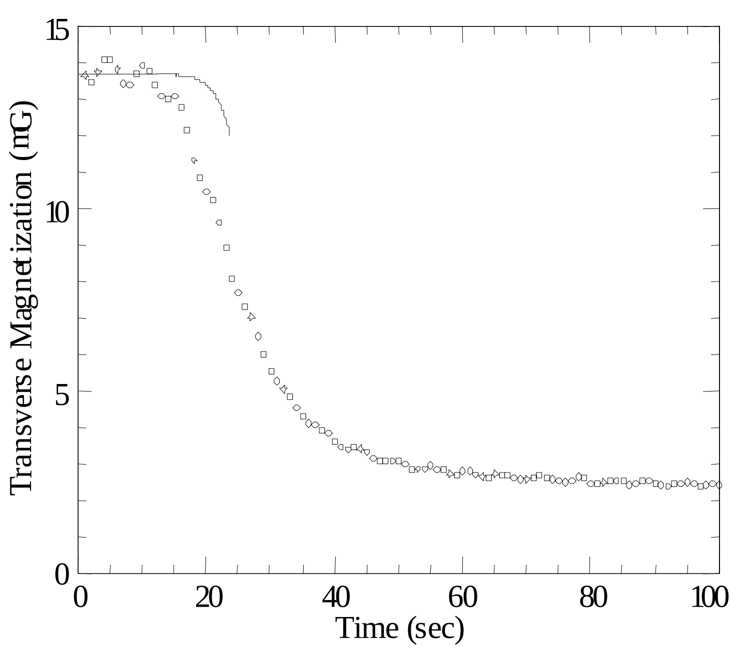
$$M_y = -\gamma M_0 G z t$$

Exponential amplification due to dipolar fields

$$M_y = -\frac{15}{8\sqrt{2}\pi} G \sinh(\beta t)\ z$$

$$\beta = \frac{8\sqrt{2}\pi}{15} \gamma M_0$$

Magnetization gradients grow exponentially with time constant $\beta^{-1} \sim 1$ sec



G = 1.4 mG/cm

$\beta = 0.2\ \mathrm{sec}^{-1}$

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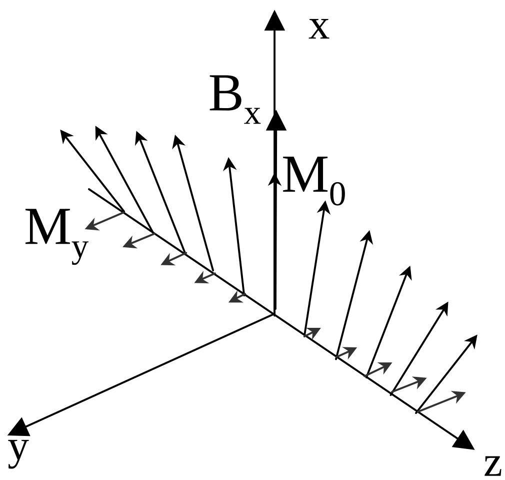
Effect of a magnetic field in the *x* direction in the rotating frame

Rotating Frame



- Rotates magnetization gradient M_y

- $\beta = \frac{8\sqrt{2}\pi}{15}\gamma M_0$ replaced with

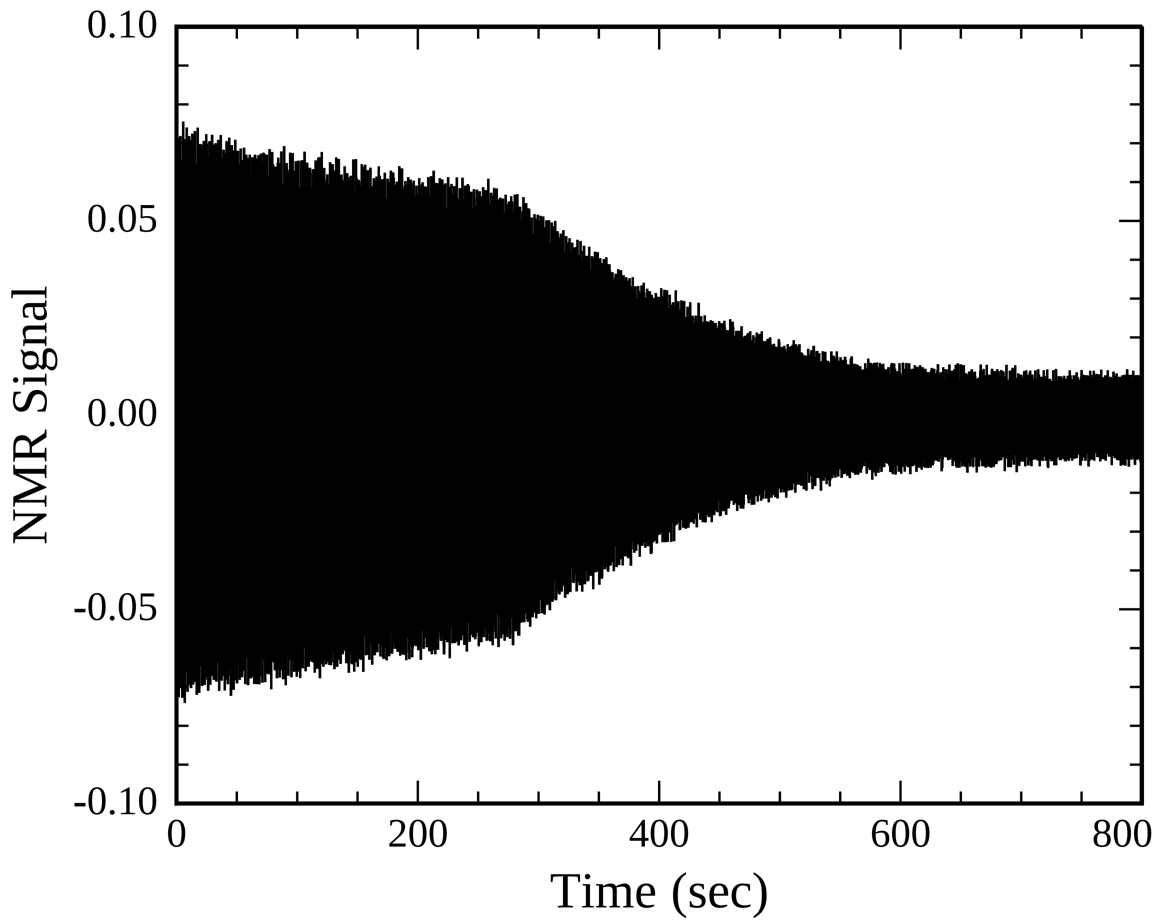
$$\beta = \sqrt{\left(\frac{16\pi}{15}\gamma M_0 - \gamma B_x\right)\left(\frac{8\pi}{15}\gamma M_0 + \gamma B_x\right)}$$

β real or imaginary depending on size of B_x relative to M_0

Suppression of Exponential Gradient Sensitivity

- In CPMG sequence reduce pulse length by 3%

  ⇒Small rotation around *x* axis with each pulse



  ⇒Delays onset of non-exponential decay by a factor of 10

SQUID Detection

- SQUIDs much more efficient than traditional RF pick-up coil at low magnetic fields

  ⇒Signal proportional to Φ, not dΦ/dt

- Magnetic field sensitivity of Low-T_c SQUID

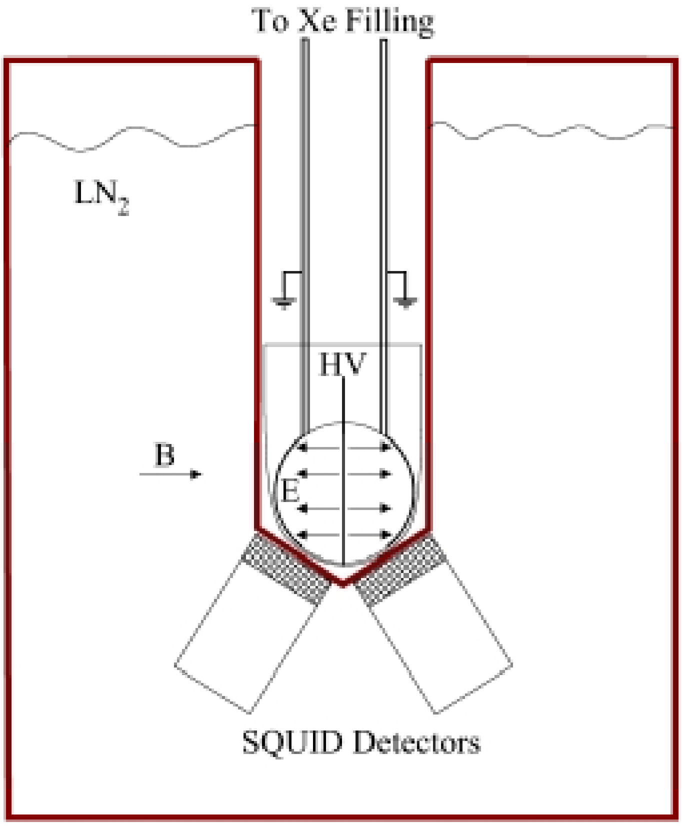
  10^{-11} G/√Hz at 10 Hz

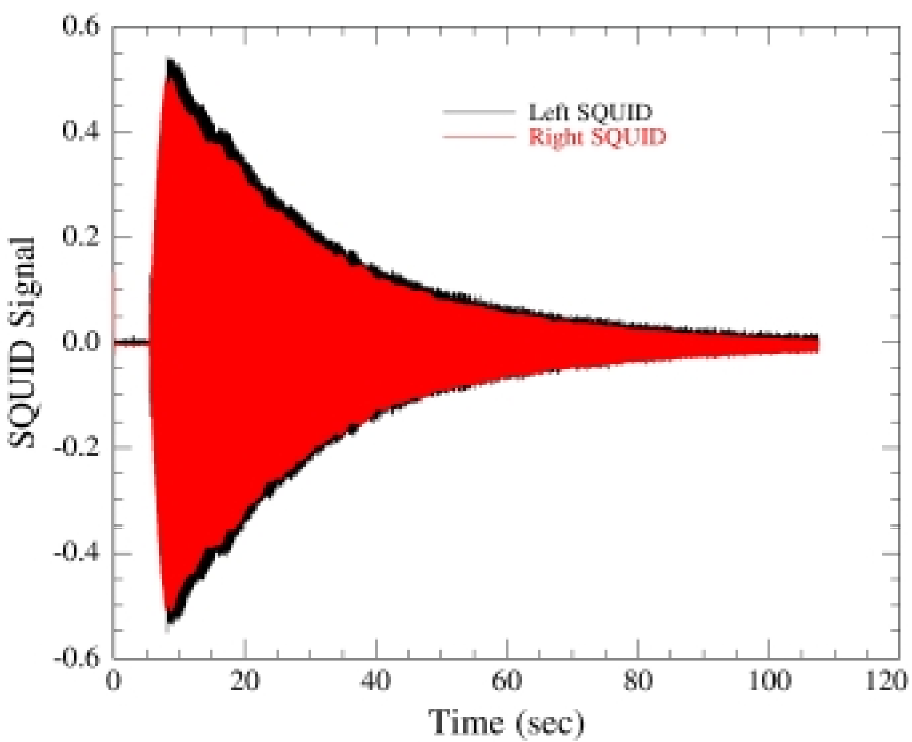
- Commercially available High-T_c (YBCO) SQUID

  3×10^{-10} G/√Hz at 10 Hz

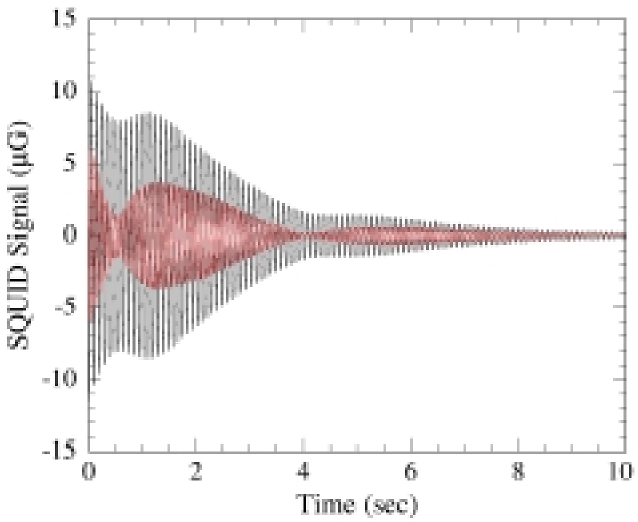
- Use five-layer magnetic shields with shielding factor of 10^6

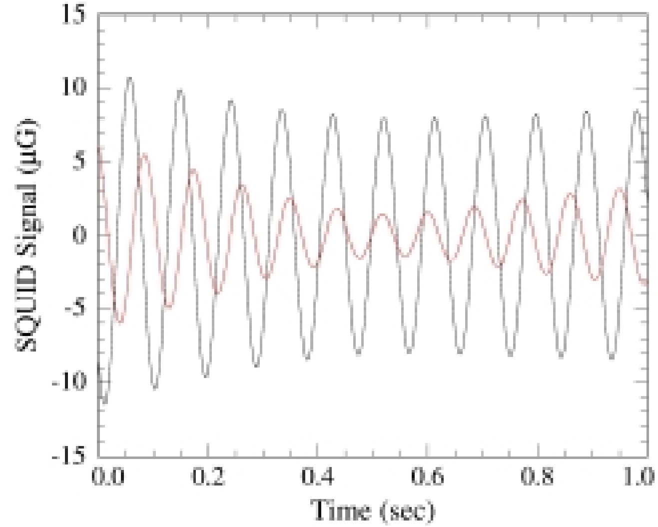
Two-SQUID Arrangement



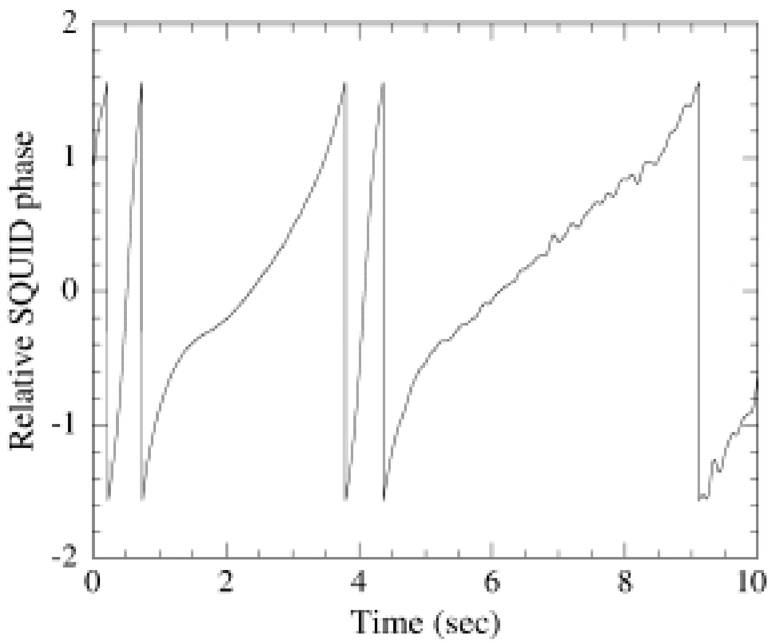


Real-time phase monitoring



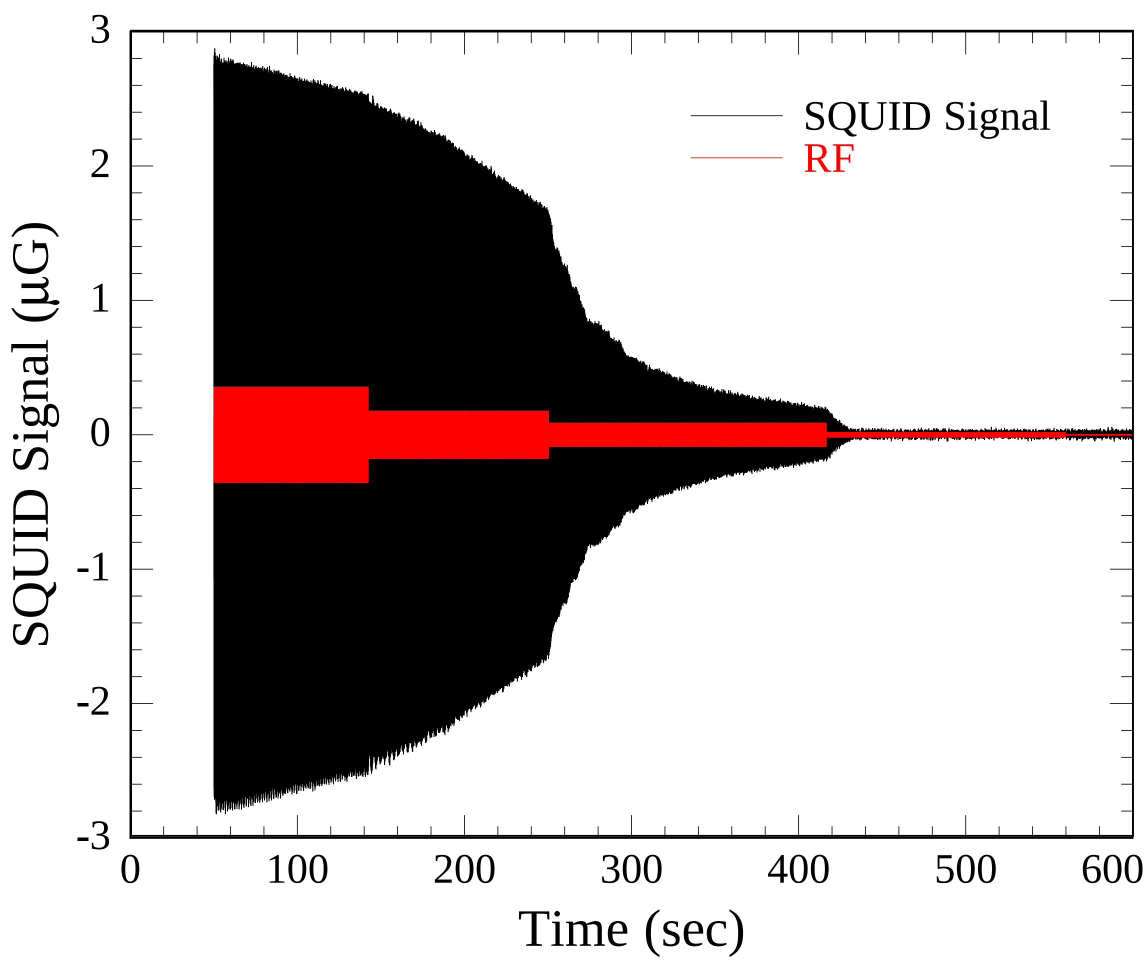


$$\phi = Arc\tan\left(Filter\left[\frac{SQ_1(t)SQ_2(t-\tau)}{SQ_1(t)SQ_2(t)}\right]\right), \tau = 1/4f$$



Controlled Spin Dephasing

- By sweeping RF frequency adiabatically to resonance tip spins to 90°
- Ramp down RF amplitude (B_x) until spins begin to dephase



- Rely on phase difference between SQUIDs to measure exponentially enhanced dephasing and prevent dramatic polarization drops using feedback

What is the expected sensitivity?

- Conservative parameters:

P_{Xe}= 5%, Ab = 26%, E = 60kV/cm, τ = 10s, T= 1day

⇒Statistics: $d_{Xe} < 10^{-33}$ *e* cm

⇒Magnetic field sensitivity - similar to Hg

  * Higher electric field compensates for lower CP sensitivity

⇒Smaller sample size and faster electric field reversal (10 sec vs. 200 sec)

⇒Leakage currents reduced by low temperature, clean surfaces

⇒SQUID sensors can be used for magnetic field monitoring.

  * LHe SQUIDs preferred due to higher sensitivity and lower 1/f noise

- $d_{Xe} \sim 10^{-30}$- 10^{-31} *e* cm with LN_2 SQUIDs
- $d_{Xe} \sim 10^{-33}$ *e* cm with LHe SQUIDs

Conclusions

- A new limit on ^{199}Hg EDM puts stringent constraints on CP violation beyond the Standard Model.

- Additional improvements in sensitivity are expected with 4-cell configuration.

- Liquid ^{129}Xe , with its long transverse spin relaxation time, will allow large improvements in EDM sensitivity.

- Exponential enhancement of magnetic field gradients will allow to come close to shot noise limit.

Collaborators

- Clark Griffith
- Matt Swallows
- Jim Jacobs
- Norval Fortson

^{199}Hg

- Micah Ledbetter
- Marty Boyd
- Mathew Chasan

^{129}Xe

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