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Title: Search for a permanent electric dipole moment of ~~mercury atoms~~ 199 HG

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Form 836 (7/06)

Search for a permanent electric dipole moment of ~~mercury atoms~~ 199 HG

Abstract:
Experimental searches for permanent electric dipole moments (EDMs) provide extremely sensitive probes for physics beyond the standard model. The three main classes of EDM searches are: measurements on bare neutrons; measurements on paramagnetic atoms or molecules, mainly sensitive to the electron EDM; and measurements on diamagnetic atoms, mainly sensitive to CP-violating interactions between nucleons. The most sensitive diamagnetic experiment is performed on Hg-199 atoms at the University of Washington in Seattle. A four vapor-cell measurement of the Hg EDM was recently completed, resulting in an upper bound |d(Hg)| < 3.1x10^-29 e cm, a factor of seven improvement on the previous limit. Details on the experimental technique and results will be given, along with theoretical implications of the new limit, and prospects for improvement

New Limit on the Permanent Electric Dipole Moment of ^{199}Hg

W. Clark Griffith
Los Alamos National Laboratory

Collaborators:
Tom Loftus, Blayne Heckel, and Norval Fortson:
Physics Department, University of Washington
Matt Swallows: *JILA, University of Colorado*
Michael Romalis: *Princeton University*

Outline

EDM searches: neutron, electron, diamagnetic atoms

UW ^{199}Hg experiment – technique/apparatus details

Experimental Dataset

Systematic Effects

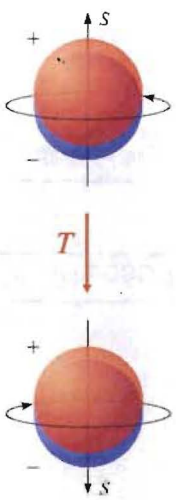
New Upper Bound on the EDM of ^{199}Hg

Improved limits on *CP*-violating parameters

Summary

The Search for an EDM

A permanent EDM violates T :



Crucial point 1:

The Standard Model generates EDMs far too small to see.

Therefore, finding an EDM would be proof of new physics.

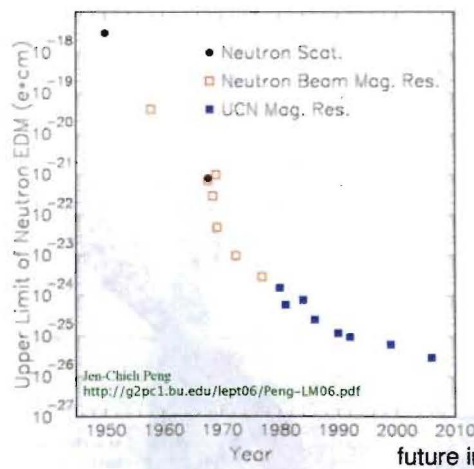
Search for an EDM of the neutron began over 50 years ago, so far no luck.

Crucial point 2:

Theories of physics beyond the Standard Model → EDMs large enough to see with current experiments.

Therefore, keep on looking!

EDM searches: the neutron



best limit:

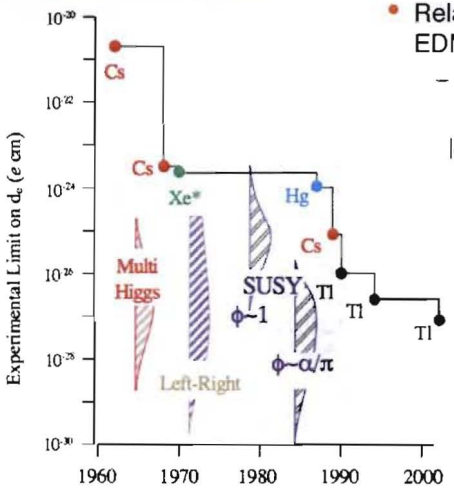
$|d_n| < 3.0 \times 10^{-26}$ e cm (2006)

C. A. Baker *et al*, PRL **97**, 131801 (2006).

UCN + ^{199}Hg comagnetometer (Sussex/ILL)

future improvements:
continuation of UCN+199Hg (PSI)
neutrons in liquid He (SNS and ILL)
•Expected sensitivity ~ 10^{-28} e cm

EDM searches: the electron



- Relativistic enhancement of the electron EDM in heavy paramagnetic atoms
  - best limit is from Thallium:

$$d_{Tl} = -585\, d_e$$

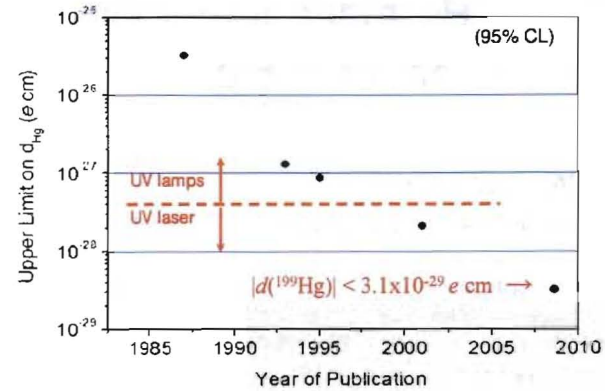
$$|d_e| < 1.6 \times 10^{-27}\ e\ \text{cm (2002)}$$

B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, PRL 88, 071805 (2002).

- Other approaches:
  - polar molecules
    YbF (Imperial College)
    WC (Mich.), ThO (Harvard)
    HfH^+ (JILA) ....
  - laser cooled Cs (Penn St., Texas)
  - solid state measurement? (Amherst, Yale)

EDM searches: diamagnetic atoms

- Diamagnetic atoms ($^1S_0$ ground state) with finite nuclear spin (I) are sensitive to the EDM of the nucleus



Shielding reduces the effect of the nuclear dipole:

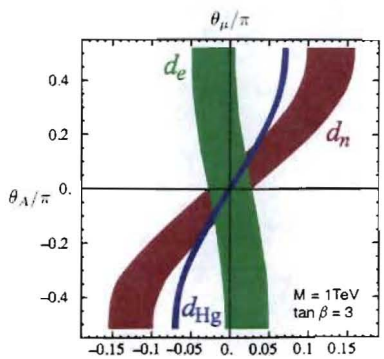
$$d_{atom} \propto d_{nuc}\underbrace{\left[Z^2\left(\frac{r_n}{a_0}\right)^2\right]}_{\approx 10^{-3}}$$

other approaches:
liquid Xe (Princeton)
trapped Ra (Argonne,KVI)
Rn (Mich./TRIUMF)

S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, PRL **59**, 2275 (1987).
J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, PRA **52**, 3521 (1995).
M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, PRL **86**, 2505 (2001).
W.C. Griffith, M.D. Swallows, T.L. Loftus, M.V. Romalis, B.R. Heckel, and E.N. Fortson, PRL **102**, 101601 (2009).

From the ^{199}Hg EDM to fundamental physics

^{199}Hg Atomic EDM
↓ *Atomic Physics* ↓
^{199}Hg Schiff Moment
↓ *Nuclear Physics* ↓
CP-Violating Pion-Nucleon Coupling
↓ *QCD* ↓
Quark Chromo-EDMs $\tilde{d}_q$
↓ *SUSY, etc ...* ↓
Model-Dependent CP-Violating Parameters



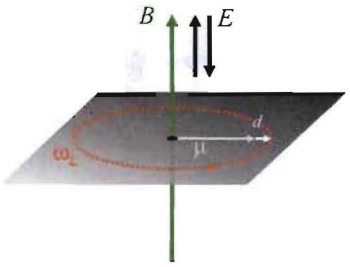
T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999). Update A. Ritz (2009).

From the ^{199}Hg EDM to fundamental physics

^{199}Hg Atomic EDM → Semileptonic Interactions: $C_S\, C_P\, C_T$
↓ *Atomic Physics* ↓ → Hyperfine Coupling: *d(e)*
^{199}Hg Schiff Moment
↓ *Nuclear Physics* ↓ → Nucleon EDMs: *d(n), d(p)*
CP-Violating Pion-Nucleon Coupling
↓ *QCD* ↓ → CP-Violating QCD Term: $\bar{\theta}_{QCD}$
Quark Chromo-EDMs $\tilde{d}_q$
↓ *SUSY, etc ...* ↓
Model-Dependent CP-Violating Parameters

Measuring an EDM via Larmor precession

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

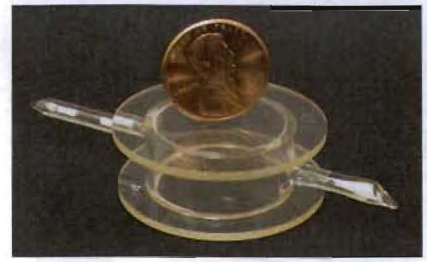


$$\omega_1 = \frac{2\vec{\mu}\cdot\vec{B} + 2\vec{d}\cdot\vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu}\cdot\vec{B} - 2\vec{d}\cdot\vec{E}}{\hbar}$$

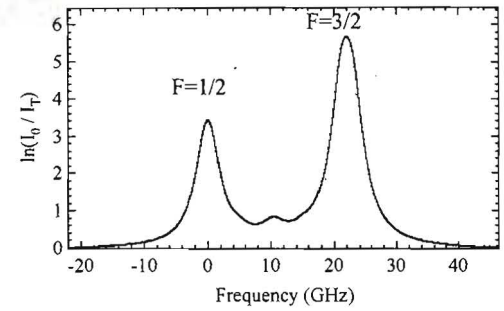
$$\Rightarrow \quad \omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}$$

^{199}Hg vapor cells

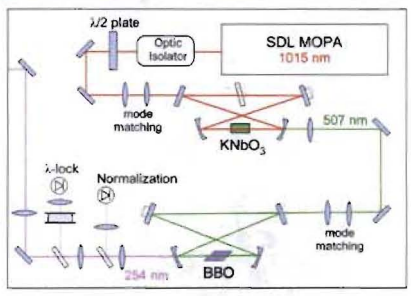


- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: 0.5 – 1 pA
- CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

Absorption scan at 254 nm
$6^1S_0 \rightarrow 6^3P_1$



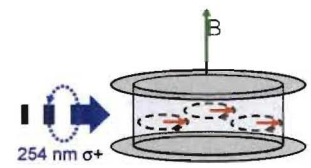
254 nm laser system

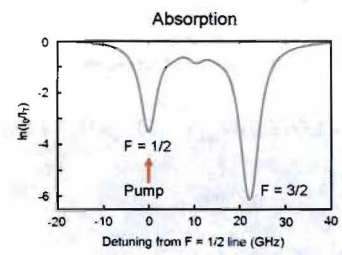


- SDL MOPA (Master Oscillator, Power Amplifier) semiconductor laser: 500 mW at 1015 nm
- First doubling stage ($KNbO_3$): 130 mW at 507.4 nm
- Second doubling state (BBO): 6 mW at 253.7 nm

Spin precession measurement

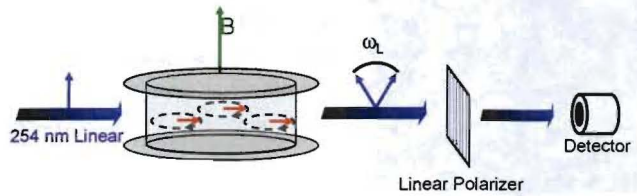
Transverse Optical Pumping

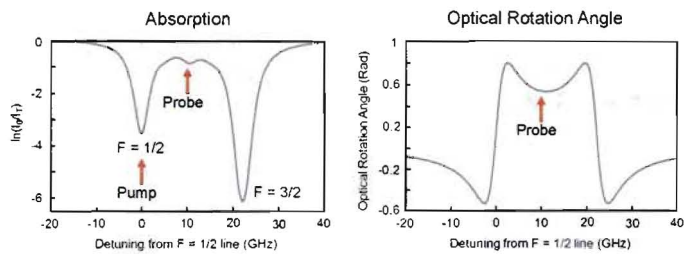




Spin precession measurement

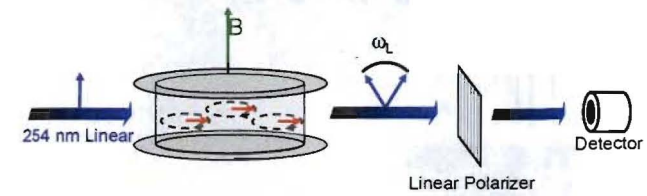
Measure ω_L via Optical Rotation

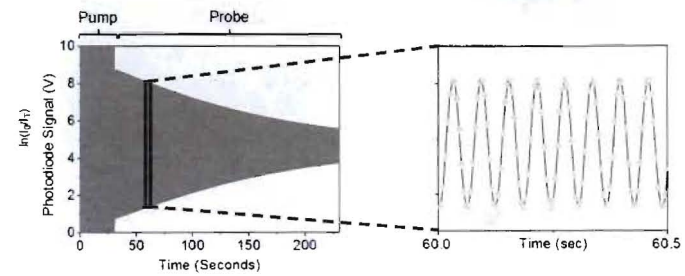




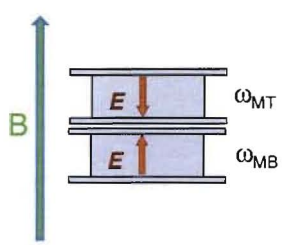
Spin precession measurement

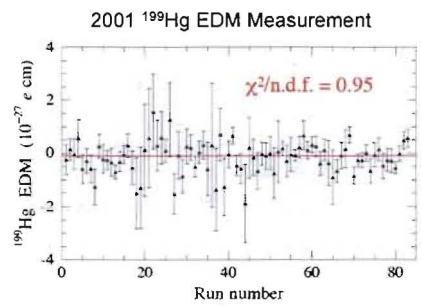
Measure ω_L via Optical Rotation





2-cell measurement





60 days of data from Feb. to Aug. 2000

→ 40,000 electric field reversals

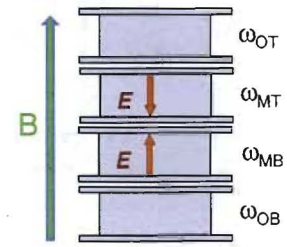
taking $\omega_{MT} - \omega_{MB}$
cancels common-mode B-field fluctuations

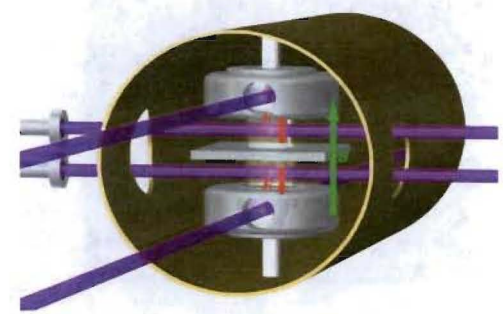
$$d_{Hg} = -(1.06 \pm 0.49_{stat} \pm 0.40_{sys}) \times 10^{-28}\ e\ \text{cm}$$

0.4 nHz

$$|d_{Hg}| < 2.1 \times 10^{-28}\ e\ \text{cm}$$

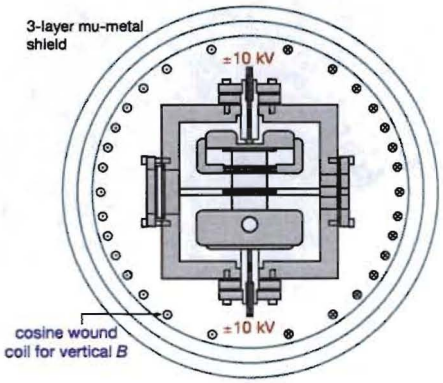
4-cell measurement

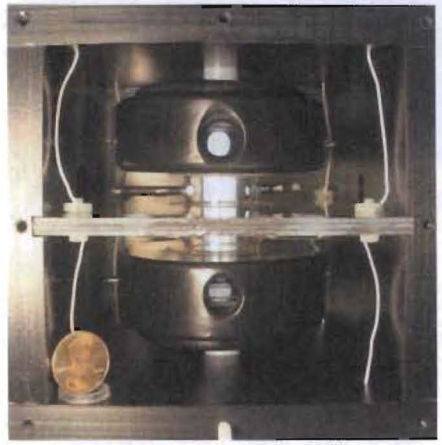




- outer cells at zero electric field – used to cancel magnetic gradient noise and check for magnetic systematics

Cell holding vessel



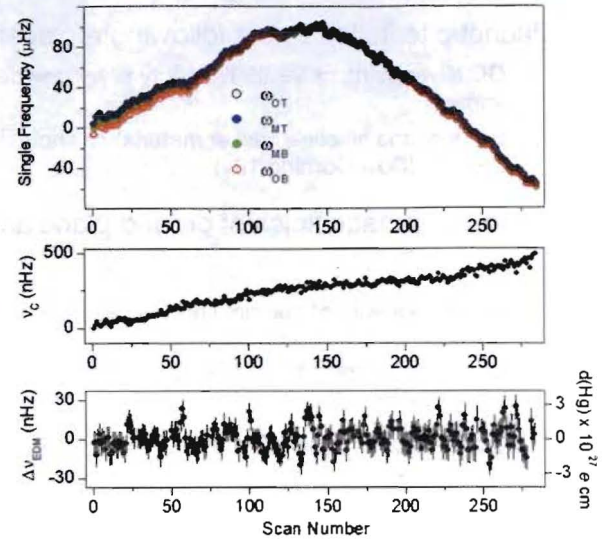


- Vessel and cell enclosing electrodes machined from electrically conductive, graphite filled polyethylene
- gold-coated fused silica groundplane between middle cells

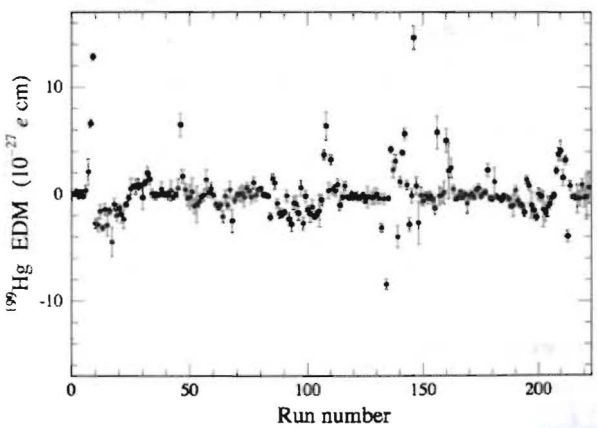
Typical 24 hour run

$$(\omega_{MT} - \omega_{MB}) - \frac{1}{3}(\omega_{OT} - \omega_{OB})$$

$$\frac{\omega_i - 2\omega_{i+1} + \omega_{i+2}}{4}$$



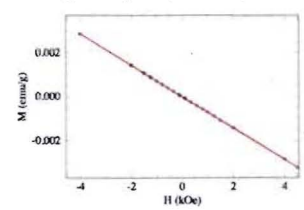
4 cell data: 2002 – 2004



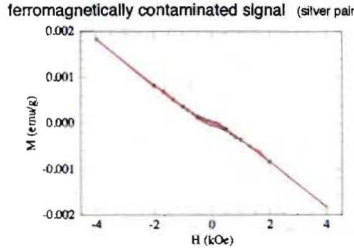
- 160 days of data with Electric field in 220 data runs.
- About 100 of these runs shows signs of a significant HV correlated frequency shift

SQUID magnetometer materials testing

diamagnetic signal (Dow Corning 184 silicone)

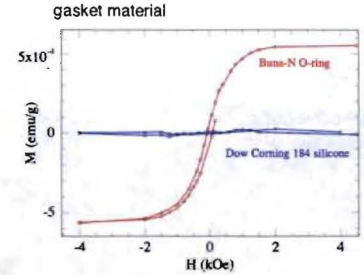


ferromagnetically contaminated signal (silver paint)

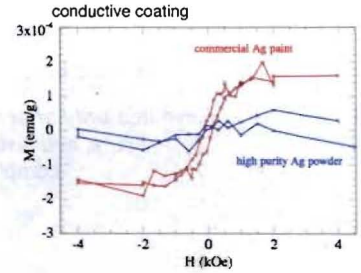


After linear background subtraction:

gasket material



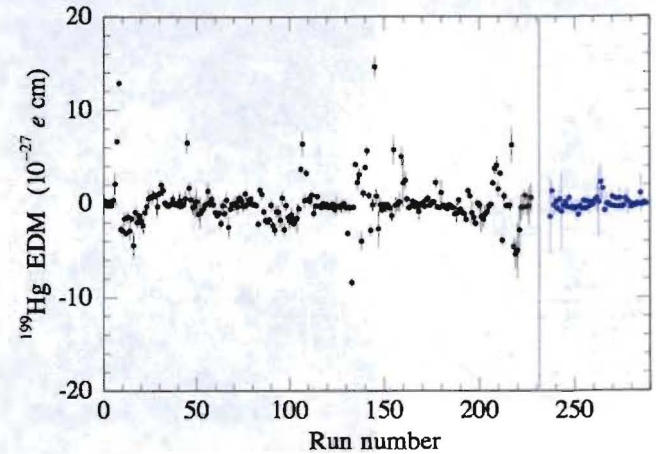
conductive coating



Major changes

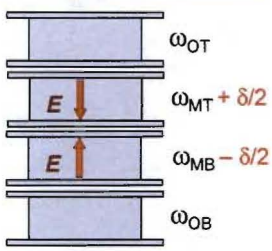
- Magnetic tests led to the following replacements:
  - GC silver paint → 99.999% purity silver powder in Testor's model varnish
  - Buna-N and silicone gasket material → "homemade" silicone gaskets (Dow Corning 184)
- Improved surface finish of ground plane and electrodes
- Cleaning
  - All components of cell-holding vessel soaked in HCl to remove possible ferromagnetic contaminants.
  - Only nonmagnetic tools (plastic, titanium, or TiN coated) used when handling the vessel and cells.
- Filter with 3 nm pore size installed in vessel purge-gas line

Result of changes



- No large resolved signals since cell-holding vessel cleaning/rebuild (blue points).

Blind analysis of HV correlated signals



Analysis program adds an unknown, HV-correlated, EDM-mimicking offset $\delta/2$ to the middle cell frequencies

Produced an EDM-like signal between $\pm 2 \times 10^{-28}\ e\ \mathrm{cm}$

Masked the measured EDM

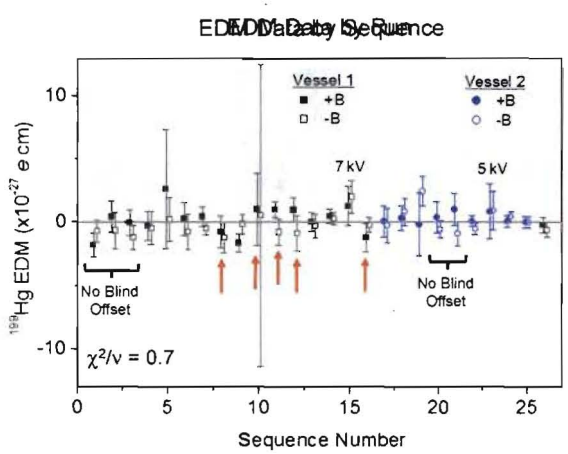
Revealed ***only after*** the data collection, data cuts, and error analysis were complete

Measurement hierarchy

- **Scan:** Individual pump / probe cycle
- **Run:** Roughly 24 hours, several hundred scans (or HV reversals)
- **Sequence:** Self-contained collection of runs
- 8-10 Dipole HV runs (+-+-+...), Equal number of B=F and B=R → EDM Data
- 1 or more Quadrupole HV (+0-0+0-0 ...) → Constrain E^2 Systematics
- Several Dipole HV runs with tipped B-Field → Constrain $(\vec{v} \times \vec{E})$ Systematics
- **Additional Runs:**
- High probe beam intensity, tipped probe beam polarization

Complete Dataset: 332 runs (~ 98,000 HV Reversals)

Raw dataset



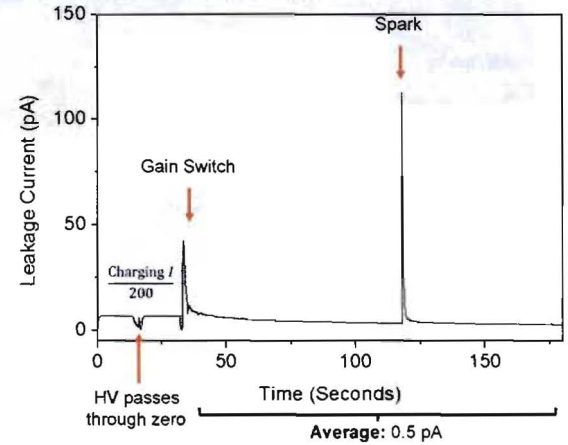
Excluded Sequences

No Blind Offset

Micro-Sparks

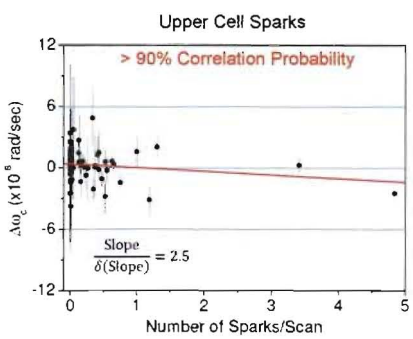
Spark correlations / cuts

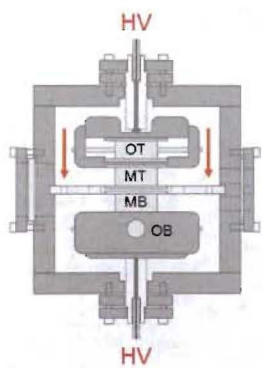
Current collected on the groundplane top-side:



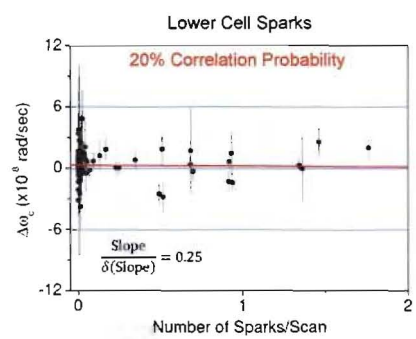
- Sparks occurred in sequences using periodically purged N_2 in vessel
- No sparks for periodically purged SF_6 or continuously flowed N_2

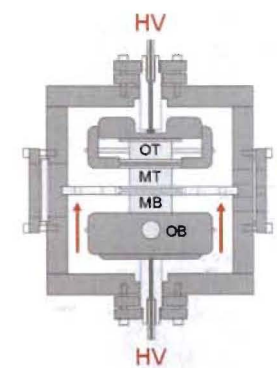
Spark correlations / cuts



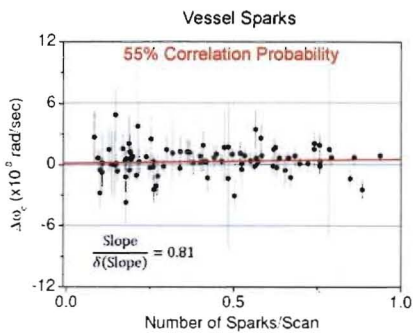


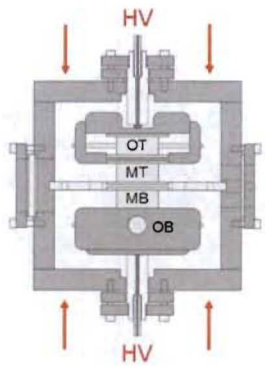
Spark correlations / cuts





Spark correlations / cuts



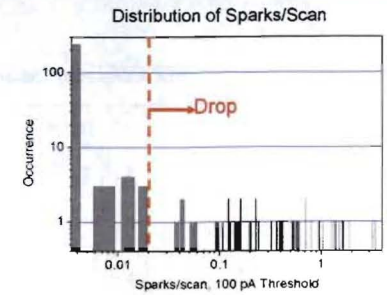


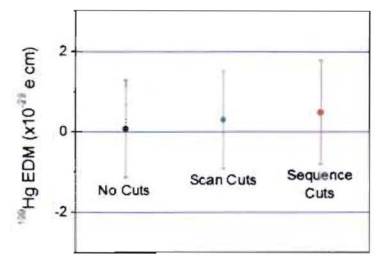
Spark correlations / cuts

Schemes for Data Cuts

Eliminate any scan with sparks
- Reconstruct the individual runs

Eliminate runs with sparks
- Drop sequences with incomplete B-Flips
- Equivalent to dropping all 5 sequences





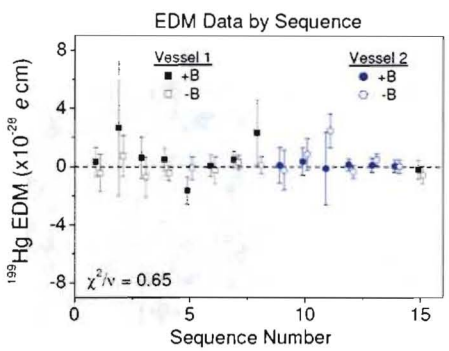
Agreement Between Spark Cut Central Values

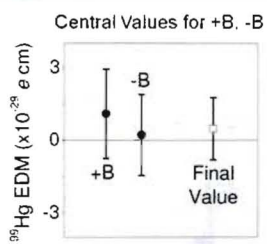
1.8×10^{-30} *e* cm

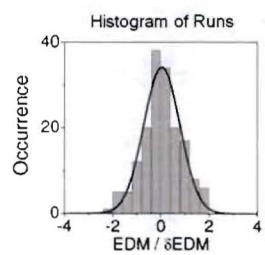
Shift Due to Spark Cuts

$< 4.2 \times 10^{-30}$ *e* cm

Final dataset







$d(^{199}\mathrm{Hg}) = (0.49 \pm 1.29_{stat}) \times 10^{-29}$ *e* cm

0.1 nHz (~ 7 ppt)

Systematic checks and error budget

No Statistically Significant Dependence on:
- Vapor cells
- Electrodes
- Vessels

Systematic Error Budget

Source	Error (10^{-30} *e cm*)
Leakage Currents	4.53
Parameter Correlations	4.31
Spark Analysis	4.16
Stark Interference	1.09
E^2 Effects	0.62
Charging Currents	0.40
Convection	0.36
$(\vec{v} \times \vec{E})$ B-Fields	0.18
Berry's Phase	0.18
Quadrature Sum	**7.63**

99% of Total Error

Leakage currents

Worst Case Scenario of Helical Current Flow

$$\delta(d_{Hg}) \approx 3.1 \times 10^{-29}\ (e\ \mathrm{cm})/(\mathrm{pA-Turn})$$

Average Single-Cell Current: 0.42 pA

Effective Current: √2(0.42 pA) = 0.59 pA

Maximum Helical Path (cell geometry): ½ Full Turn

Averaging Due to Cell Flips: Factor of 2

4.5 x 10^{-30} e cm

Parameter correlations

Parameters:

Larmor Precession Fits

- Single Cell
- spin amplitudes
- lifetimes
- relative phases
- frequency errors
- background

Apparatus Sub-Sustems

- UV Laser System:
- power
- frequency
- drive current
- piezo control voltages
- External B-Fields:
- 3-axis fluxgate magnetometer
- B-field coil currents:
- Main coil and 3 shim coils

calculate HV correlation & correlation with $\Delta\omega_{EDM}$ → 1-σ Limit from Product

↓

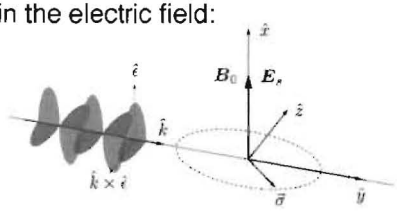
Quadrature Sum

4.3x10^{-30} e cm

Stark-induced interference

- Static electric field mixes $M1$ and $E2$ components into the $6^1S_0 \rightarrow 6^3P_1$ intercombination line
  - causes change in absorption linear in the electric field:

$$\frac{\delta\alpha}{\alpha} = (a_{E2} + a_{M1})(\hat{\varepsilon}\cdot\vec{E}_s)(\hat{k}\times\hat{\varepsilon})\cdot\hat{\sigma}$$



- 1992 calculation: $a = -6.6 \times 10^{-8}\ (kV/cm)^{-1}$

S.K. Lamoreaux and E.N. Fortson, PRA, 7053 (1992).

$$\delta\omega_{SI} \approx 7.2 \times 10^{-30}\ (e\,\mathrm{cm/degree})$$

misalignment of ε, E_s, and B_0 < ~3° over dataset

Stark-induced interference

- Our measurements currently give

$(a_{M1} + a_{E2}) = (0.39 \pm 0.32_{Stat}) \times 10^{-8}\ (\mathrm{kV/cm})^{-1}$

$$\delta\omega_{SI} \approx 3.6 \times 10^{-31}\ (e\,\mathrm{cm/degree})$$

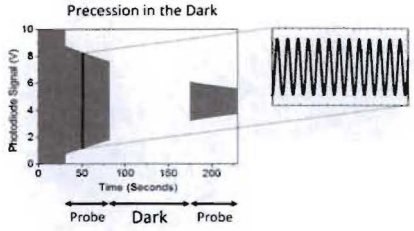
→ 1.1 x 10^{-30} e cm

- New calculation: K. Beloy, V.A. Dzuba, and A. Derevianko, arxiv:0903.1660

2009: $(a_{M1} + a_{E2}) = 0.80 \times 10^{-8}\ (\mathrm{kV/cm})^{-1}$

1992: $(a_{M1} + a_{E2}) = -6.6 \times 10^{-8}\ (\mathrm{kV/cm})^{-1}$

- Stark interference can be suppressed by switching to a "precession in the dark" measurement



Improved bounds on *CP*-violating parameters

$$d(^{199}\mathrm{Hg}) = (0.49 \pm 1.29_{stat} \pm 0.76_{sys}) \times 10^{-29}\ e\ \mathrm{cm}$$

$$|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\ \mathrm{cm}\ (95\%\ \mathrm{CL})$$

Parameter	^{199}Hg bound	Best other limit		
$\tilde{d}_q$(cm)	6×10^{-27}	n:	3×10^{-26}	Quark Chromo EDMs: 5x
d_p(e cm)	7.9×10^{-25}	TlF:	6×10^{-23}	Proton EDM: 76x
C_S	5.2×10^{-8}	Tl:	1.3×10^{-7}	Semi-Leptonic Interactions: C_S: 2.5x
C_P	5.1×10^{-7}	TlF:	3×10^{-4}	C_P: 590x
C_T	1.5×10^{-9}	TlF:	4.5×10^{-7}	C_T: 300x
$\bar{\theta}_{QCD}$	3×10^{-10}	n:	1×10^{-10}	QCD Phase
d_n(e cm)	5.8×10^{-26}	n:	2.9×10^{-26}	Neutron EDM
d_e(e cm)	3×10^{-27}	Tl:	1.6×10^{-27}	Electron EDM

For ^{199}Hg : $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$ while for n: $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$

Confidence Levels: ^{199}Hg (95%), n (90%), ^{205}Tl (90%), TlF (95%)

Summary

- EDM searches in the neutron, paramagnetic, and diamagnetic systems provide a valuable test for new sources of *T*-violation.
- 4-cell ^{199}Hg EDM measurement has improved the diamagnetic upper bound by 7x
- Implementing apparatus upgrades:
  - monitor leakage current into four quadrants on ground plane – reduces circular current in ground plane, reveals helicity of leakage
  - SnO_2 instead of gold coating on groundplane – lower Johnson currents in immediate cell vicinity
  - vessel/electrode redesign to lower spark rate
  - non-conductive form for B_0 coil
  - balanced polarimeters
  - investigating precession in the dark scheme

Summary

- Anticipate upgrades finished in 2011
- ~2-3 years of data collection to an expected 3-5 times improvement in statistical sensitivity
- Current UW team:

Norval Fortson
Blayne Heckel

Post-Doc: Nathan Kurz
Grad Students: Brent Graner
Chen Yi