Improvements to the Mercury Electric Dipole Moment Experiment

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Motivation

Charge conjugation (C): particle → antiparticle

Parity inversion (P): $\mathbf{r} \rightarrow -\mathbf{r}$

Time reversal (T): $t \rightarrow -t$

CP violation[1]:

- Required for baryogenesis
- Exists in the Standard Model, but not enough to account for matter-antimatter asymmetry

Image credit: Steve Jurvetson via Wikimedia Commons

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[1] A. Riotto and M. Trodden, Annu. Rev. Nucl. Part. Sci. **49**: 35-75 (1999)

Experimental Overview

Mercury electric dipole moment (EDM):

- Nonzero EDM violates CP symmetry
- CPT theorem: CP violation $\iff$ T violation (as long as Lorentz invariance holds)

Hamiltonian:

- $H = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$
- $\boldsymbol{\mu}, \mathbf{d}, \mathbf{B}$ are pseudovectors; $\mathbf{E}$ is a vector

	$\boldsymbol{\mu}$	$\boldsymbol{B}$	$\boldsymbol{d}$	$\boldsymbol{E}$
Original	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
T-reversed	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$

Experimental Overview

- ^{199}Hg: $^1S_0$ electronic ground state and nuclear spin 1/2

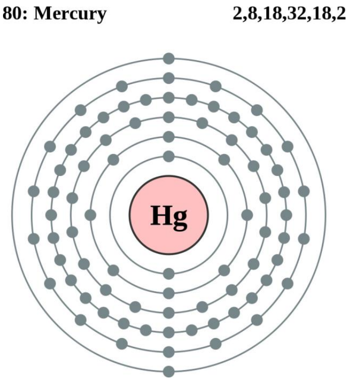


Image credit: http://chemistry.about.com/od/elementfacts/ig/Atom-Diagrams/Mercury-Atom.htm

Experimental Overview

- In external magnetic field, $H = -\boldsymbol{\mu} \cdot \mathbf{B}$
  $\implies$ Larmor frequency: $h\nu_L = 2\mu B$
- Adding a possible EDM and E-field (anti)parallel to $\mathbf{B}$,

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

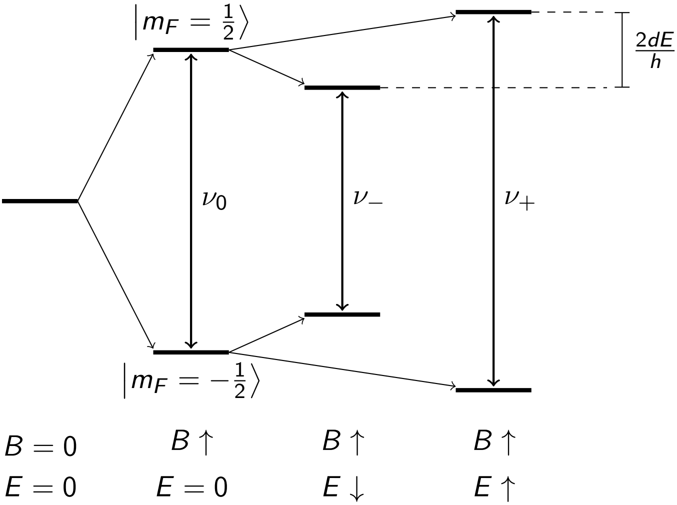
- If EDM exists, it points along nuclear spin axis and

$$h\nu_L = |2\mu B \pm 2dE|$$

- Look for shift in ν_L when $\mathbf{E}$ is reversed relative to $\mathbf{B}$,

$$\Delta\nu = \nu_{\text{parallel}} - \nu_{\text{antiparallel}} = \frac{4dE}{h}$$

Experimental Overview



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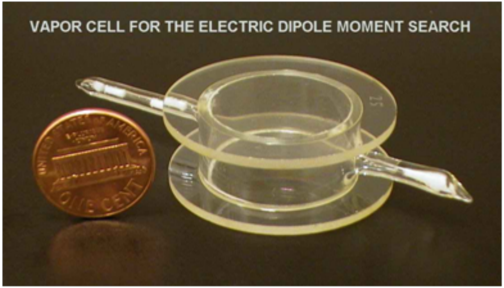
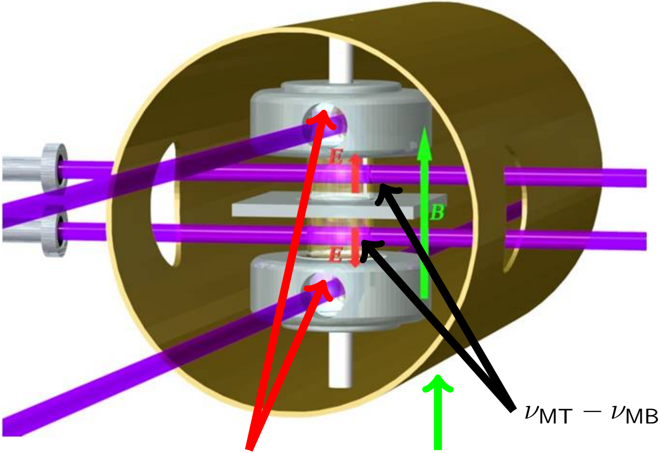
Experimental Setup



Experimental Setup

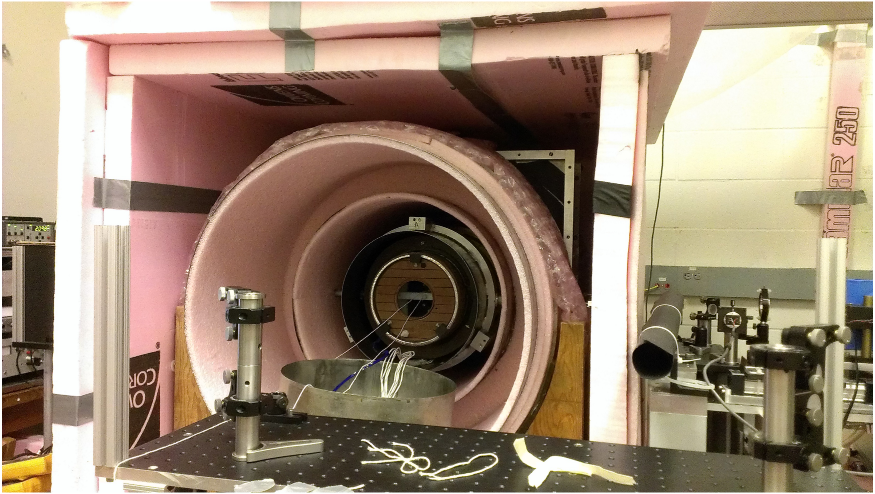
Image credit: Clark Griffith



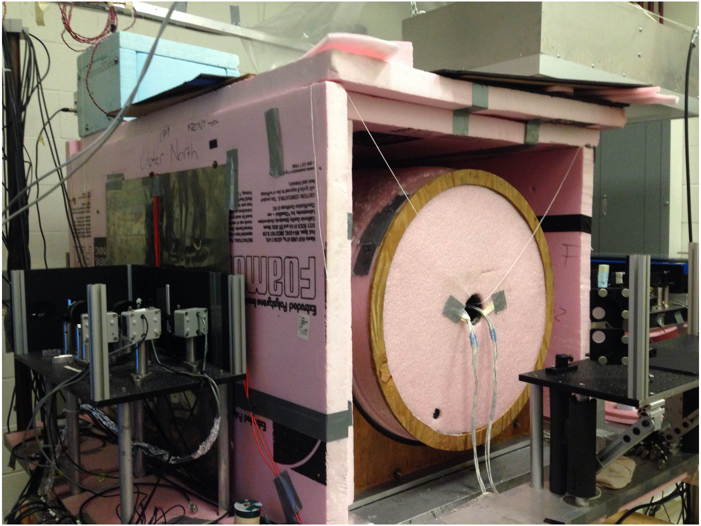
$$\nu_{\mathrm{MT}} - \nu_{\mathrm{MB}} = \frac{4dE}{h}$$

$$E = \pm 10\ \mathrm{kV/cm}, \qquad B = 10\ \mathrm{mG}$$

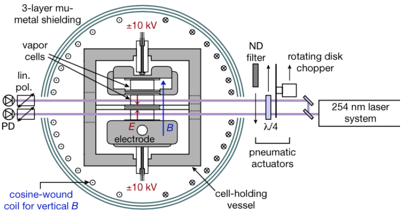
Experimental Setup

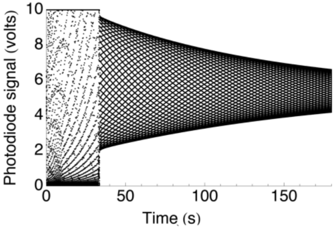


Experimental Setup



Measurement Sequence





Pump phase ($\sim$ 30 s):

- Use circularly polarized light to optically pump Hg atoms on the $^1S_0(F = 1/2) \rightarrow {}^3P_1(F = 1/2)$ line at 254 nm
- Chop pump light at ν_L to build up spin polarization normal to $\mathbf{B}$

Probe phase ($\sim$ 150 s):

- Switch to linear polarization, detune from transition, attenuate beam
- Hg spin precession causes Faraday rotation at the Larmor frequency

Frequency Combos and Analysis

- To obtain Larmor frequencies, fit each photodiode signal to

$$I(t) = A\sin(\omega t + \phi)e^{-\Gamma t} + C$$

- Outer cells have $\mathbf{E} = 0$: used to look for systematics
- The frequency combination

$$\Delta\nu_{\text{combo}} = \Delta\nu_{\text{EDM}} = \nu_{\text{MT}} - \nu_{\text{MB}} - \frac{1}{3}\left(\nu_{\text{OT}} - \nu_{\text{OB}}\right)$$

is sensitive to the EDM, while canceling first and second order magnetic field gradient noise in the y-direction

Previous result

- The last generation of the experiment found

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

- Interpret as an upper bound of $|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\ \mathrm{cm}$

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New dataset

- Expect factor of 4 improvement on EDM bound
- Currently, “B-even” effect is largest systematic error

"*B*-Even" Systematic

- Can run with B pointing up or down; $E = 6$ or 10 kV/cm

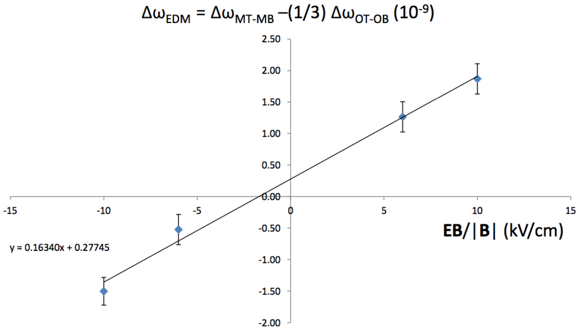

Image credit: Brent Graner

- EDM is proportional to slope – line should pass through 0!
- B-independent offset is partially resolved: $\sim 2\sigma$

“B-Even” Systematic

Possible causes of the B-even effect:

- Some component of the B-field doesn’t flip
- Cell-micromotion correlated with HV
- Other ideas: Shields relaxing, B_0 not stable

Analysis:

- OT, MT contribute much more to the effect
- Do they see more gradient?

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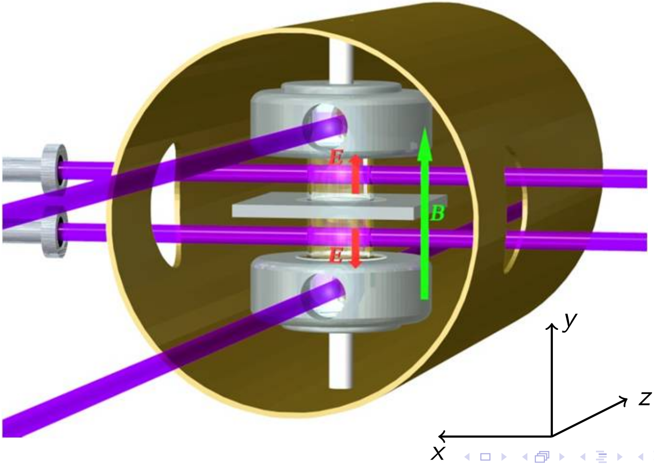
Setup

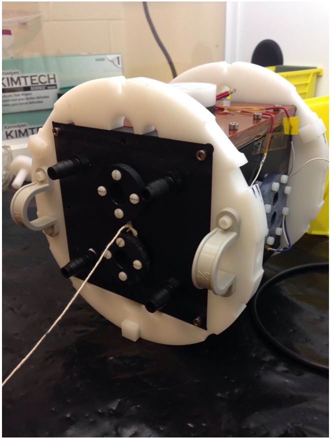
- Want to measure gradients in x, z directions by translating cells

Image credit: Clark Griffith

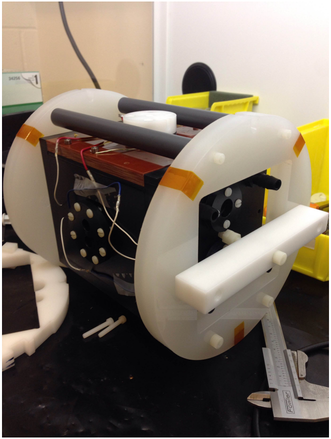


Setup

Original vessel:

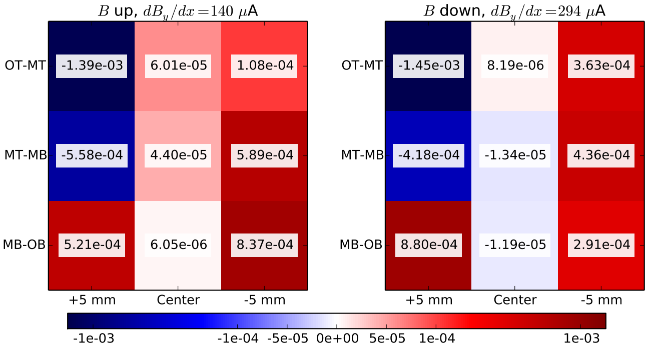


Translation apparatus:



4-cell measurement of dB_y/dx

- With $\mathbf{E} = 0$, cells act as magnetometers
- Look at frequency differences between cells
  - Common-mode rejection (drift)
  - Calculations done with cell differences
- Note: largest gradients on top, B reverses well



Magnetic field gradients in the x-direction

B up, $dB_y/dx = 140\ \mu$A

	+5 mm	Center	-5 mm
OT-MT	-1.39e-03	6.01e-05	1.08e-04
MT-MB	-5.58e-04	4.40e-05	5.89e-04
MB-OB	5.21e-04	6.05e-06	8.37e-04

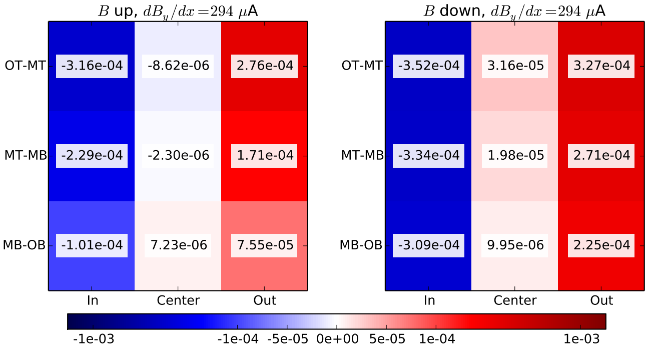
B down, $dB_y/dx = 294\ \mu$A

	+5 mm	Center	-5 mm
OT-MT	-1.45e-03	8.19e-06	3.63e-04
MT-MB	-4.18e-04	-1.34e-05	4.36e-04
MB-OB	8.80e-04	-1.19e-05	2.91e-04

Measuring dB_y/dz

- Do a similar measurement, but translating in the z-direction...

Magnetic field gradients in the z-direction



B up, $dB_y/dx = 294\ \mu$A

	In	Center	Out
OT-MT	-3.16e-04	-8.62e-06	2.76e-04
MT-MB	-2.29e-04	-2.30e-06	1.71e-04
MB-OB	-1.01e-04	7.23e-06	7.55e-05

B down, $dB_y/dx = 294\ \mu$A

	In	Center	Out
OT-MT	-3.52e-04	3.16e-05	3.27e-04
MT-MB	-3.34e-04	1.98e-05	2.71e-04
MB-OB	-3.09e-04	9.95e-06	2.25e-04

Interpretation

- Focus on x-direction (larger gradients)

Non-reversing component of B:

- Quantify non-reversing part of B-field using the feedthrough to our EDM signal
- $B_{\text{even}}/B_{\text{odd}} \approx 0.002$ – not enough to explain the B-even effect

Cell micromotion:

- Can estimate magnetic field gradients in the apparatus: $\sim 0.2\ \mu\text{G}/\text{cm}$
- Frequency shifts $\sim 10^{-10} \implies$ cell motion ~ 10 nm could cause B-even effect

How to improve this?

- Cell micro-motion isn't a problem if B-field is uniform

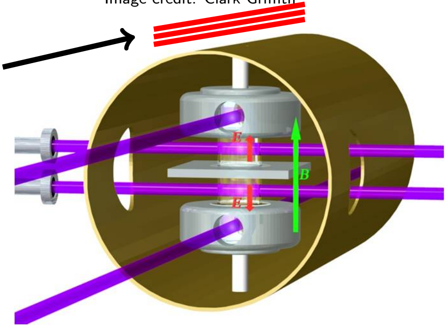


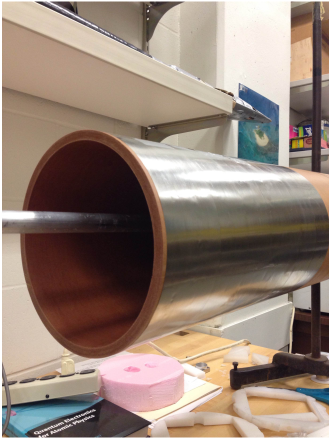
Image credit: Clark Griffith

Shield welds!

- Top two cells contribute most to B-even systematic
    - Measured larger gradient on the top two cells
    - Closest to the welds in the magnetic shields!

Solution: Mu-metal foil magnetic shield

- Plan: add additional layer of magnetic shielding (innermost layer)
- Use 2 mil thick mu-metal foil, so no welds
- Calculate[2] increase in shielding factor of 3-5 times (depending on μ_r of the foil)
- More uniform shield means more uniform field



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[2] T. J. Sumner, J. M. Pendlebury and K. F. Smith, J. Phys. D: Appl. Phys **26** 1095 (1987)

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Conclusion

- Measured magnetic field gradients to explore the cause of our B-even systematic
- Plan to add new thin and more uniform magnetic shield to make the field more uniform
- Figure out a way to take similar measurements translating in the y-direction

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