A Search for a Permanent Electric Dipole Moment of the Electron in a Solid State System

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Shapiro’s proposal -- using a solid state system to measure $e\text{EDM}$


$d_e = (0.81 \pm 1.16) \times 10^{-22}$ e-cm
Features of solid state eEDM experiment

**Pros:**

- High number density of bare electrons $\sim 10^{22}/\text{cm}^3$.
  
  PbO Cell
  \[ N = nV \sim 10^{16} \]
  
  Tl Beam:
  \[ N = nV \sim 10^8 \]

- Electrons are confined in solid $\Rightarrow$ No motional field effect.

  \[ B_{\text{motional}} = \nu \times E \]

- Solid state sample:
  - Large magnetic response.

**Cons:**

- Solid state sample:
  - High dielectric strength.

- Concerns
  - Parasitic, hysteresis solid state effects might limit the sensitivity to the EDM signals.
What are required to have Macroscopic T Nonconservation?

- Proposed “EuS” near its Curie point
- Requirements:
  - System can be found in which intrinsic EDM’s are not screen out at the atomic level.
  - Chemical bonding does not obliterate the atomic EDM.
  - An external electric field will actually be felt by atoms in the interior of the sample.
  - The T-nonconserving effects which we seek to observe cannot be mimicked by effects associated with broken inversion symmetry in the crystal.
Figure of Merit

- Sensitive magnetometers
  - Superconducting Quantum Interference Device (SQUID).
  - Atomic cell (non-linear Faraday effect).
- Measure induced magnetic flux:

\[ \Delta \Phi = BA = \left( \frac{\chi_m d E^*}{\mu_a} \right) A \]

- Paramagnetic susceptibility \( \chi_m \)
- Pick-up coil area
- Effective field, large dielectric constant K.
- Large \( \chi_m \)
- Large \( A \)
- Large \( E \)
- A paramagnetic insulating sample

\[ d = \alpha d_e, \text{ enhancement factor } \alpha \propto Z^3 \]
New experiment

Gadolinium Gallium Garnet (Gd₃Ga₅O₁₂) polycrystalostal

- Gd³⁺ in GGG
  - 4f⁷ 5d⁰ 6s⁰ (7 unpaired electrons).
  - Atomic enhancement factor = -4.9±1.6.
- Langevin paramagnet.
- Dielectric constant ~ 12 (or 30).
- Low electrical conductivity and high dielectric strength
  - Volume resistivity = 10¹⁶ Ω-cm.
  - Dielectric strength = 10 MV/cm (amorphous sample).
- Cubic lattice.

Better SQUID design

Higher E field: 10kV/cm

Large Sample size: 100 cm³

EDM Enhancement Factor
of electrons in Gd\(^{3+}\) in garnet crystal


\[ d_a = K_{\text{atom}} K_{\text{CF}} d_e \]
\[ \Rightarrow -2.2 \times 9.5 d_e = -20.9 d_e \]

\[ \Delta \varepsilon = -20.9 d_e E^{\text{int}} = \frac{-20.9}{30} d_e E^{\text{ext}} \]
\[ \Rightarrow 0.7 d_e E^{\text{ext}} \]

FIG. 3. A schematic two-dimensional picture for penetration of 2p\(_\sigma\) orbitals of O\(^{2-}\) inside the shifted Gd\(^{3+}\).
A simple estimate of EDM Sensitivity

- **EDM signal:** $\Phi_p = 17\mu\Phi_0$ per $10^{-27}$e-cm. 
  - with $10\text{kV/cm}$, $T=10\text{mK}$, $A=100\text{ cm}^2$ around GGG
- **SQUID noise:** $\Delta\Phi_{sq} = 0.2\mu\Phi_0/\sqrt{t}$ (research quality)
- **Flux transfer** = $\Phi_{sq}/\Phi_p = \sqrt{(L_{sq}L_i)/(L_p+L_i)} = 8\times10^{-3}$.
  - $L_{squid} = 0.2\ \text{nH}$.
  - $L_{pick-up} = 700\ \text{nH}$ (gradiometer)
  - $L_{input} = 500\ \text{nH}$.

- $d_e = \Delta\Phi_{sq}/\Phi_{sq} = (0.2\mu\Phi_0/\sqrt{t})/(8\times10^{-3} \times \Phi_p) \times 10^{-27}$e-cm.
  - $d_e = 1.47\times10^{-27} / \sqrt{t}\ \text{e-cm}$
- In 10 days of averaging, $d_e \sim 10^{-30}$ e-cm.
GGG X-ray Diffraction

Blue: our sample
Red: World Standard

J. Valdez and K. Sickafus, LANL
Garnet Crystalline Structure

- Garnet Structure: \( \{A_3\}[B_2](C_3)O_{12} \)
  - A \( \{ \text{dodecahedron} \} \): \( M^{3+} \)
    - \( \text{Ca, Mn, Fe, R (La,..Gd,..Lu)} \)
  - B \( \{ \text{octahedron} \} \), C \( \{ \text{tetrahedron} \} \):
    - \( \text{Fe, Ga, ...} \)

The unit cell of GdIG. The cell contains 16 Fe\(^{3+}\) ions at octahedral sites (a), 24 Fe\(^{3+}\) ions at tetrahedral sites (d), and 24 Gd\(^{3+}\) ions at dodecahedral sites (c). The oxygen ions are not shown.
Magnetic Properties of GGG ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$)

- Anti-Ferromagnetic (AF) interaction on a triangular lattice
  ⇒ Geometrically frustrated AF magnet:
  ⇒ Spin glass transition at 0.4K (Limit of temperature).

P. Schiffer, et al. PRL 73, 2500 (1994)

- Spin dynamics using muon spin relaxation
  "The system is close to ordering but remains slowly fluctuating, at least down to 25 mK".
  (Spin Glass Transition happens at a much lower T)


Possible solution: spin dilution Gd(Y)GG
Susceptibility $\chi_m$ Measurements

Traditional AC field method

- Paramagnetic susceptibility
  
  \[ \chi_m = \frac{C}{T} \quad C = \frac{N\mu_b^2}{3k_B} = 1.29 \]

  \[ N^{\text{Gd}^+} = 1.03 \times 10^{22} / \text{cm}^3 \]


The measured susceptibility is as large as expected.
Electrodes and Magnetic flux pick-up coils (planar gradiometer)

- Common mode rejection of external uniform B field and fluctuations.
- Enhancement of sample flux pick-up.

$R_1 = 2\text{cm}$
$R_2 = 2\text{cm}$
$R_3 = \sqrt{(R_1^2 + R_2^2)} = 3.42\text{cm}$
$L_G = 700\text{nH for 10}\mu\text{m dia. wire}$
$= 500\text{nH for 100}\mu\text{m dia. Wire}$
(Nb superconducting wire)

$\text{CMRR} = 238$
$\Rightarrow 0.4\% \text{ area mismatch}$
E Field

Field around electrodes in eEDM system

Electric field data from file EEDM.AM
Problem title line 1: Field around electrodes in eEDM system

E
Ex
Ey

Electric field data from file EEDM.AM
Problem title line 1: Field around electrodes in eEDM system
• Reverse HV polarity
• monitor sample for magnetization change
Instrumentation

High Voltage Electrodes: **Macor** coated with **graphite**.

Magnetic Shield:
- Superconducting **Pb** foils (2 layers)
  - S factor $> 10^9$
- High $\mu$ **Metglas** alloy ribbons in cryostat.
  - S factor $\sim 100$
- An additional cylinder of "**Conetic**" sheet outside the cryostat.
  - S factor $\sim 10$
- The whole assembly is immersed in **L-He bath**, and will be cooled by a dilution refrigerator. (3.5mW at 120mK)
E Field Modulation -- High Voltage Polarity Switch

- **Power Supply**: PS350
  - 5kV, 25W, 15ppm ripple
- **Field reversal rate**: 1~10Hz.
- **Use vacuum tubes (triode)** to handle the high voltage.
- **Turn the two tubes on/off alternatively** by driving the grid-cathode voltages to the cut-off voltage.

**Vacuum Tubes**
- **Red**: Filament drive (20kHz)
- **Blue**: Grid voltage control (Frequency control)
- **Black**: HV switch

**Diagram Notes**
- 6BK4: 15kV Insulation, 1:1
- FPT100: 15K
- LM2876TF: 20kHz, 7Vrms
- SHV: +5kV, 5mA limited
- -5kV, 5mA limited
- 200Meg: 200K
- Feedback: SHV Output +5kV
- BNC: HV monitor
Capacitors between HV shield to the chamber ground, ground plans to the chamber ground.

Alleviate the micro-sparks in HV cables from going into the electrodes.

Before Cooling

After Cooling

Replaced by surface-mount capacitors

200 kOhm

2.8 nF
Star Cryoelectronics 1165 SQUID:
- Fails after a few thermal cycles.
- Current lock mode built-in

Quantum Design DC SQUID, Model 50:
- Very sturdy
- Flux lock mode

- Closed Pb box, containing a SQUID (solder sealed)
- To pickup coil
- To PFL circuit box, Outside the cryostat
SQUID Noise Spectrum

- One layer of Pb superconducting foil
- 2 layers of Pb superconducting foil
- Background ~ Intrinsic SQUID noise
- 1/f corner of SQUID noise < 1Hz

Baseline: 27.5 μΦ₀/√Hz
Baseline: 5.8 μΦ₀/√Hz
HV monitor

Current in the ground plate

SQUID signal
SQUID signal:
(-2.68+5.5)e-7 V
(-0.66 + 2.8)e-7 V (drift corrected)

Current measured in ground planes:
(-4.6 + 0.1)e-10 A (cross talk)

de_e=(1.46 ± 6.16) × 10^{-24} e\text{-cm}

d_e=(0.81 ± 1.16)×10^{-22} e\text{-cm}

Most Run in Oct. 2006
Accumulated EDM:
(1.7 ± 5.2) × 10^{-23} e\text{-cm}
December 2005

**Flux(Phi0)**

-1.50E-006
-1.00E-006
-5.00E-007
0.00E+000
5.00E-007
1.00E-006
1.50E-006
2.00E-006
2.50E-006

**Current in ground plates**

-1.00E-003
-5.00E-004
0.00E+000
5.00E-004
1.00E-003
1.50E-003
2.00E-003

**LC1 (microA)**

**LC2 (microA)**
Instabilities in SQUID sensor output

- Adding current bypass capacitors to the ground greatly reduce the high frequency spark signals into the SQUID.

- Stability of the SQUID feedback circuit.
  - A larger RC constant of the FB circuit makes the SQUID operation less susceptible to frequent HV polarity switches.
Leakage Current

○ Flux = (-7.43 ± 2.2) μΦ₀
  ● Field = (1.28 × 10⁻¹⁴ gauss)/0.008 = 1600 f-gauss
○ 10fA, a quarter turn gives 1 f-gauss
○ I = 16 pA (to account for the field)

○ \( I_{\text{volume}} = \frac{V}{R_{\text{volume}}} \)
  ● 1kV/(10¹⁶Ωcm*1cm/12cm²) = 1.2 pA
  ● Resistivity should be larger at low T
HV supply drift

Sampled at 1kHz

Measured Ripples:
10mV/1V=1%
Beat ~ 30 Hz
Vacuum tube filament
drive: 20kHz

HV supplies spec:
(PS350, 5kV, 25W)
Ripple: 15ppm

\[ I = C \frac{dV}{dt} \]

\[ C = 28 \text{pF} \]

\[ I < 10 \text{fA} \]

\[ \frac{dV}{dt} < 3.6 \times 10^{-4} \text{V/s} = 0.36 \text{ppm/s} \]

Improve the feedback circuit
Some Observations

- Current monitor is contaminated by the channel crosstalk due to HV monitors.
  - LC < $10^{-10}$ A
- Correlation between flux and HV is not conclusive.
- SQUID flux measurement seems to be affected by the data filtering (need further investigations).
Other Systematic Effects

- **Displacement current at field reversals.**
  - Generate large field (helps to check SQUID functionality).
  - This effect is both spatially and temporally orthogonal to the true signal.
  - Magnetize materials around ???
  - Modulate the reversal frequency (or ramping time) to measure this artifact
    - the induced magnetic field is proportional to the frequency, but the electric field is not.
Solid State Effects

- T-violating EDM effect: Magnetization of the sample in response to an electric field (in the absence of an external magnetic field)

- Possible crystal effects:
  - An interaction energy linear in the magnetization could arise if
    - The material itself spontaneously breaks T invariance: choose a sample without magnetic order.
  - “dirt effect” due to residual magnetic fields: \( \mu_e S \cdot (T \cdot E) \cdot H \)

  - Related to the electric-field-dependent \( g \)-value shifts in magnetic-resonance experiments.
    \[ \mu_e |T||H| \ll d_e \]

  - Tensor \( T \) vanishes in inversion-symmetric crystal structure.
    - Point defects and substitutional impurities could pair up to restore inversion symmetry.
    - Defect concentration of 1:10^9 should impose no problem.

Conclusions

- **The current setup** is sensitive to eEDM signal $\sim 10^{-23}$ e-cm using a hour of data.

- **The prototype system** cooled to 40 mK and 2 days of data averaging should have an eEDM sensitivity of $10^{-27}$ e-cm.
  - Keep on understanding the non-zero background.
    - Eliminate channel crosstalks
    - Stabilize operations of SQUID (improved RF shields)
    - Implement multiple SQUID sensors
    - Stabilize HV supply
    - Couple to a DR

- Further improvements (towards $10^{-30}$ e-cm):
  - Scale up the prototype system
  - Spin dilution: Gd(Y)GG
  - Employ better magnetometers