Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

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Abstract: We report a factor of 12 improvement on the previous limit of the electric dipole moment of the electron (eEDM). Our reported value is $d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ e cm. This value corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ e cm with 90% confidence. Details of the experimental procedure and systematic error search are provided.

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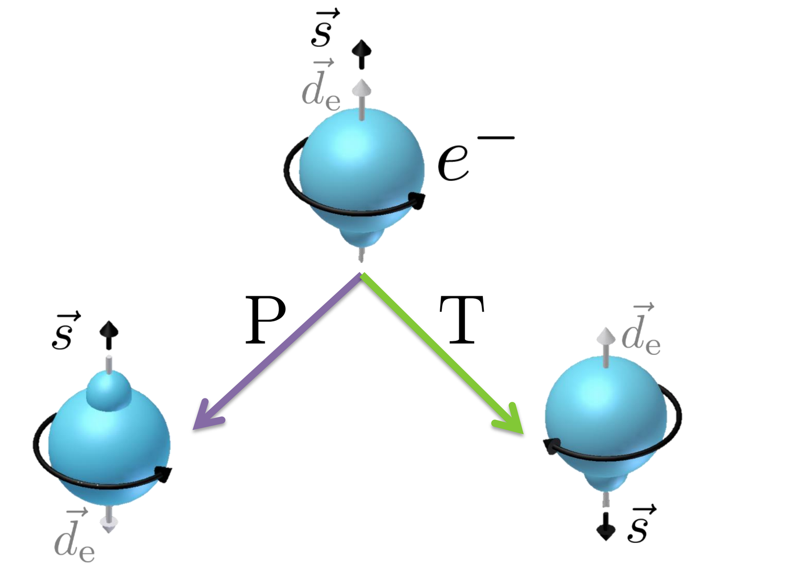
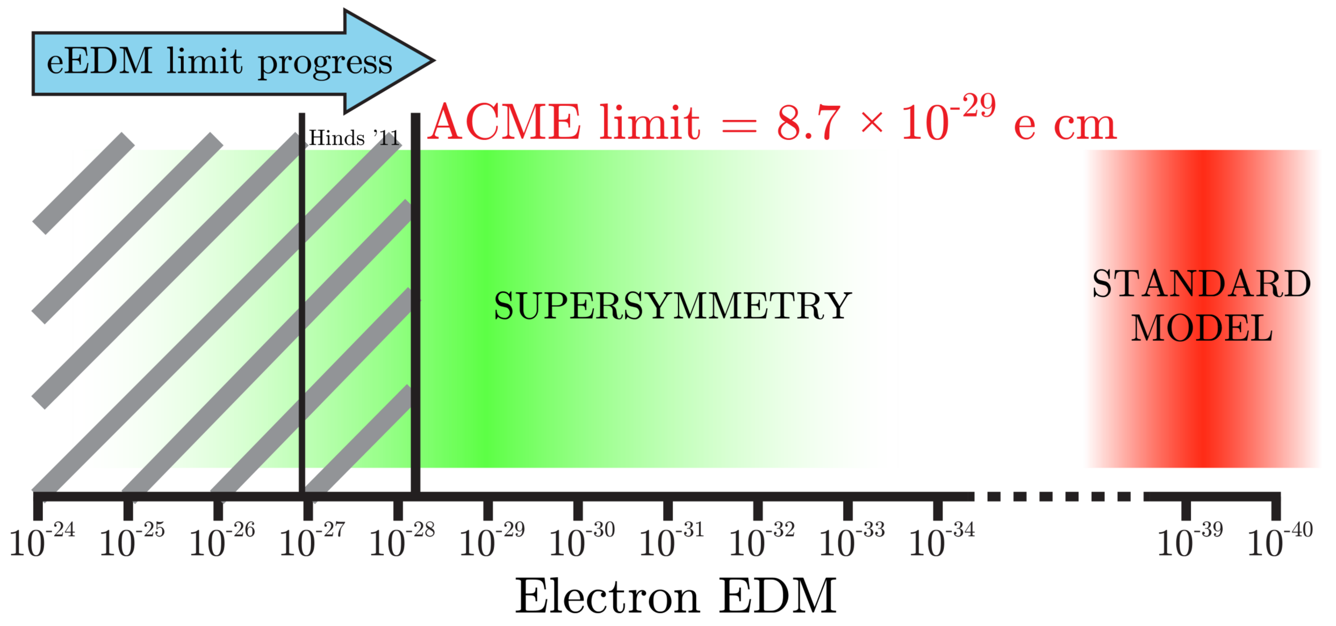
Motivation for eEDM Search

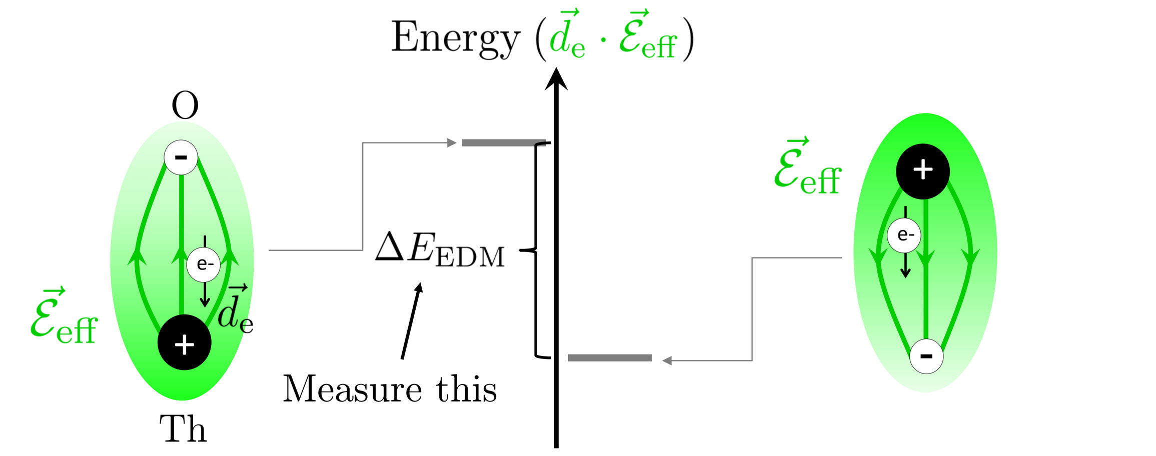
- eEDMs violate fundamental parity (P) and time (T) symmetries



- T-violation in SM small → eEDM prediction $d_e^{SM} < 10^{-38}$ e · cm
- Theories beyond SM (e.g. SUSY) predict eEDMs within a few orders of magnitude of the current experimental upper bound

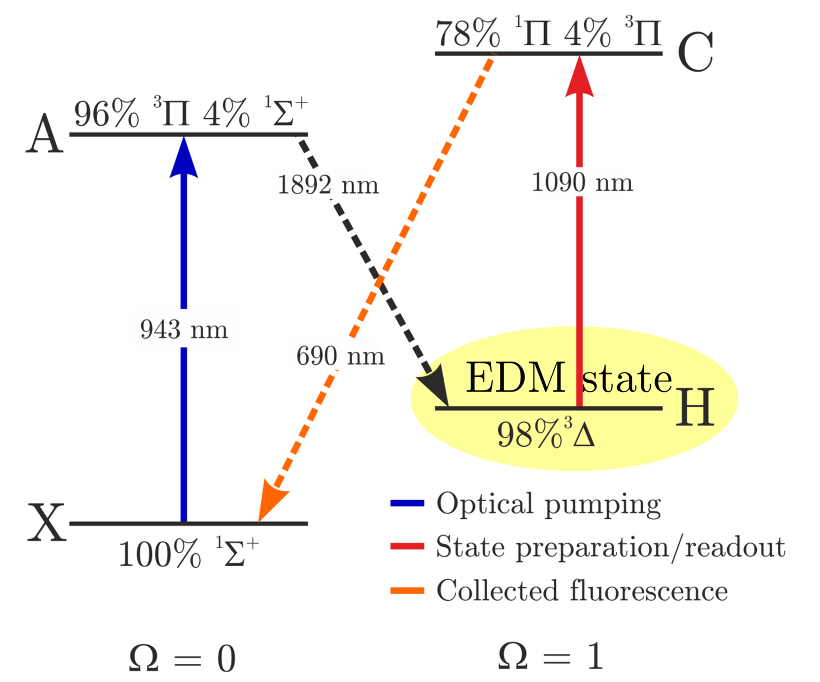


Fundamentals of eEDM Measurement

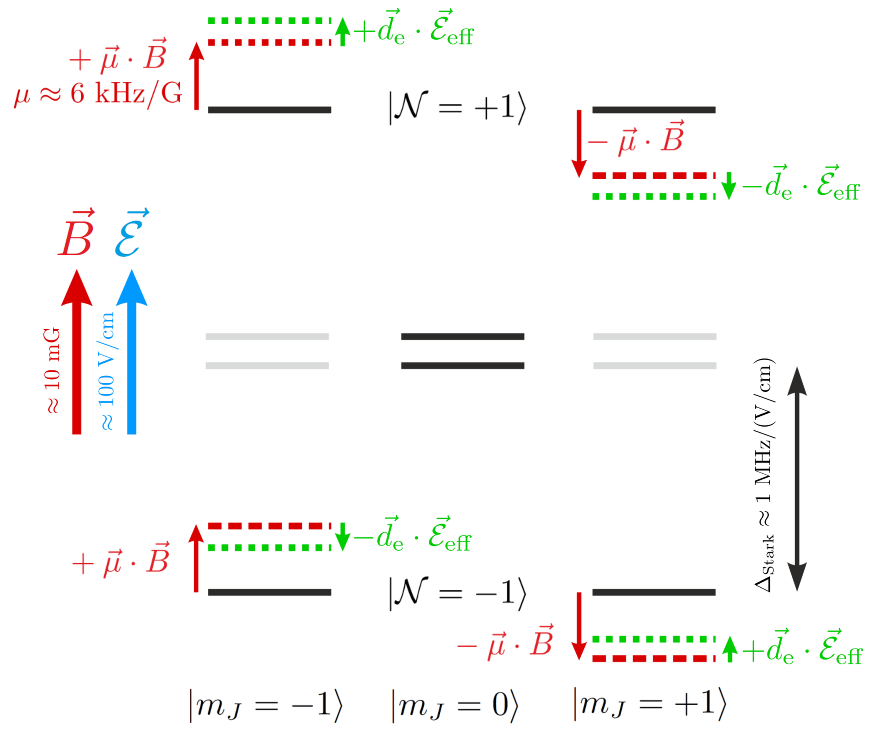


- An electric dipole moment experiences an energy shift in the presence of an electric field, such as the large E-fields present near heavy atomic nuclei
- We measure the energy splitting between two electrons oppositely oriented relative to the effective molecular field in ThO (84 GV/cm): $\Delta E_{EDM}/2 = |\vec{d}_e \cdot \vec{\mathcal{E}}_{eff}|$

ThO Level Diagram

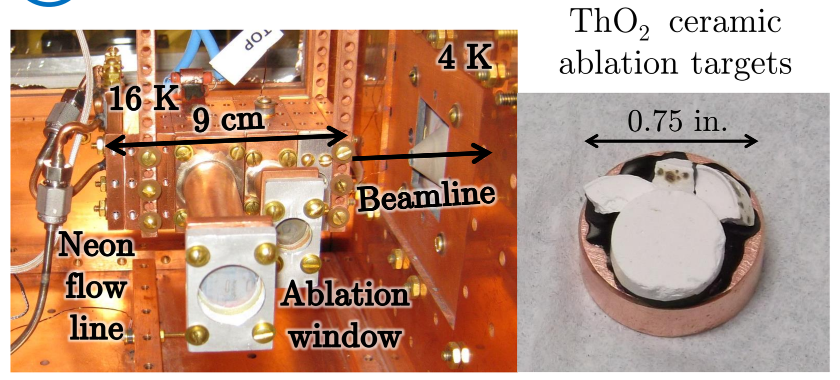


H-State Level Diagram

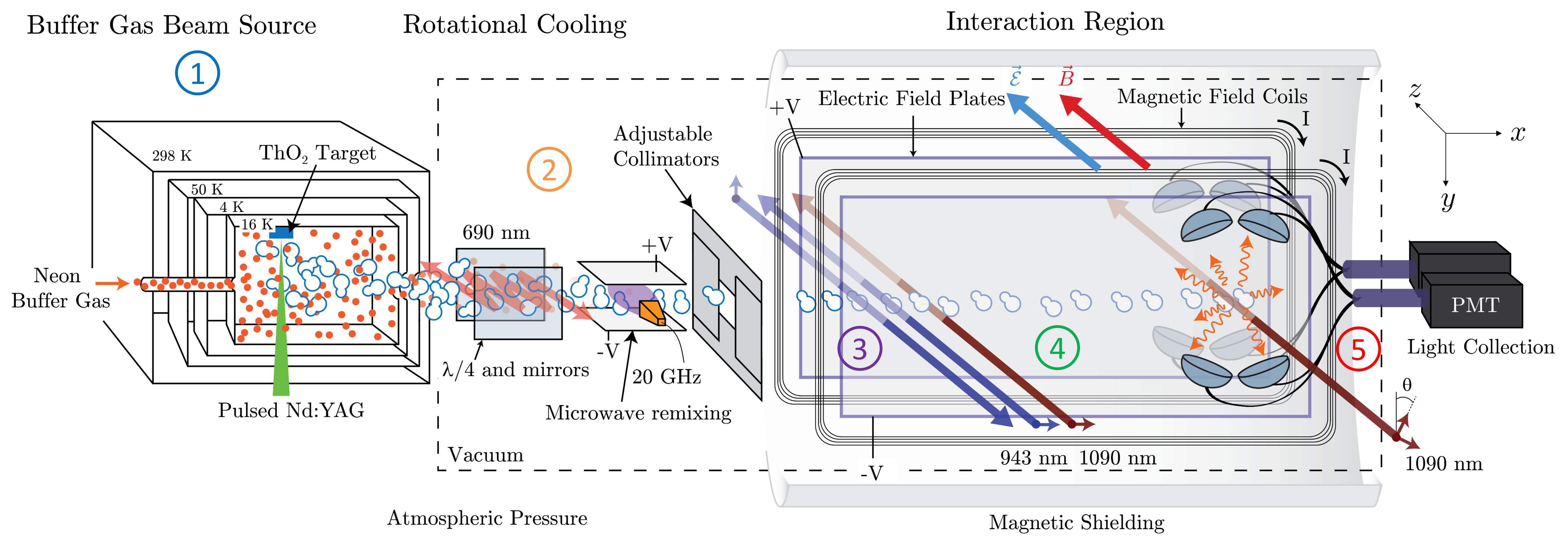


ACME Apparatus

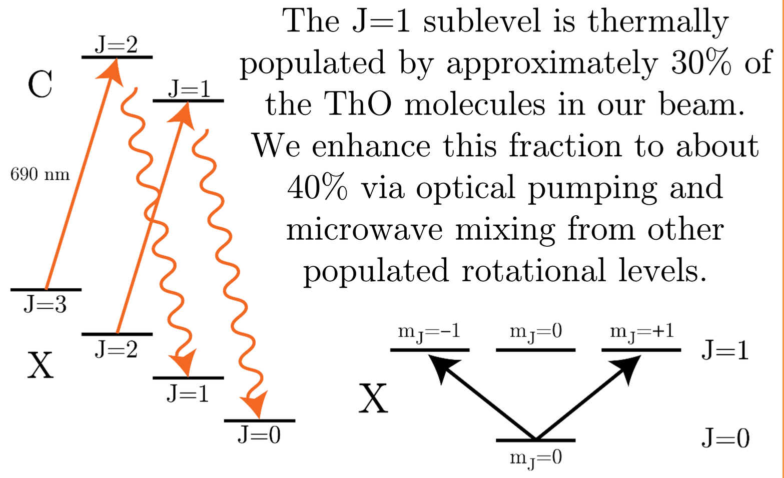
① Buffer Gas Beam Source



Gas-phase ThO molecules are introduced into a cryogenic buffer gas cell via 50 Hz pulsed laser ablation of a ceramic precursor. The molecules thermalize with the cold buffer gas and flow out of the cell aperture into a beam. The high ablation yield (10^{13} molecules per pulse) and low temperature of the beam (4 K) provide large single-quantum-state ThO fluxes of about 10^{11} sr^{-1} per pulse. The beam's relatively low velocity of 170 m/s permits a long phase accumulation time in a short interaction region.

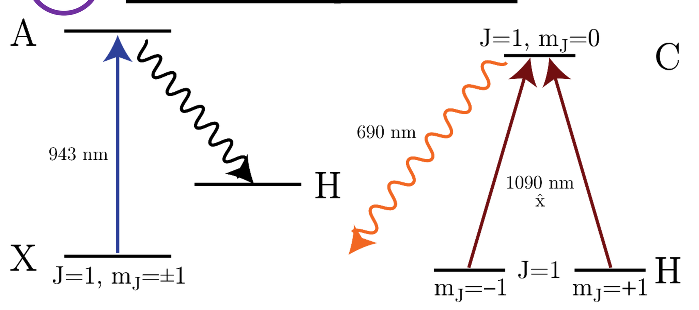


② Rotational Cooling



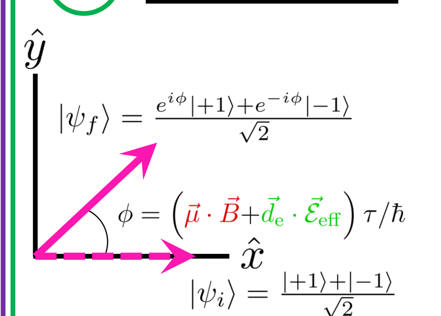
The J=1 sublevel is thermally populated by approximately 30% of the ThO molecules in our beam. We enhance this fraction to about 40% via optical pumping and microwave mixing from other populated rotational levels.

③ State Preparation



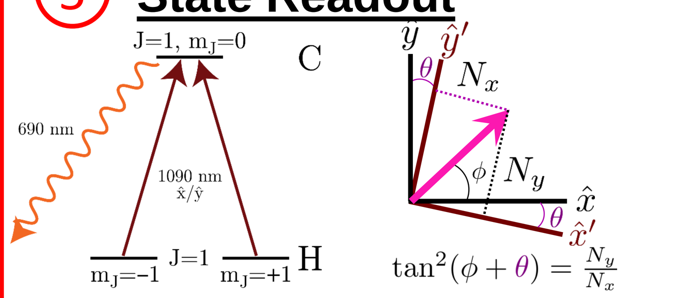
The metastable H-state is populated by optical pumping from the J=1 sublevel of the ground state. A pure superposition of m_J sublevels is then prepared by pumping on the H→C transition with linearly polarized light.

④ Precession



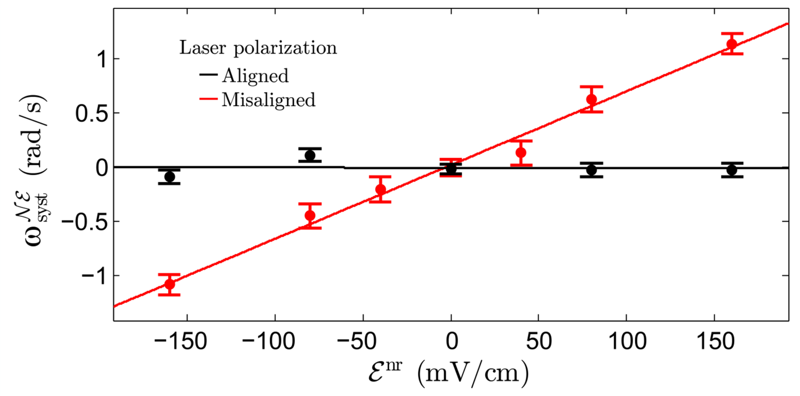
The initial spin state can be represented by a vector along the x-axis. It precesses in the field region by an angle ϕ.

⑤ State Readout



The final state is read out using a probe beam rapidly switched between orthogonal linear polarizations. This projects the state onto orthogonal basis vectors. The 690 nm fluorescence from each probe polarization is collected, allowing us to determine the phase.

Systematic Errors



A common way of identifying systematics is to exaggerate a physical parameter and measure the effect on the eEDM.

The above graph shows the effect on the eEDM-associated precession of a non-reversing electric field.

In this case the effect was minimized by aligning laser polarization with birefringent axes of our field plates.

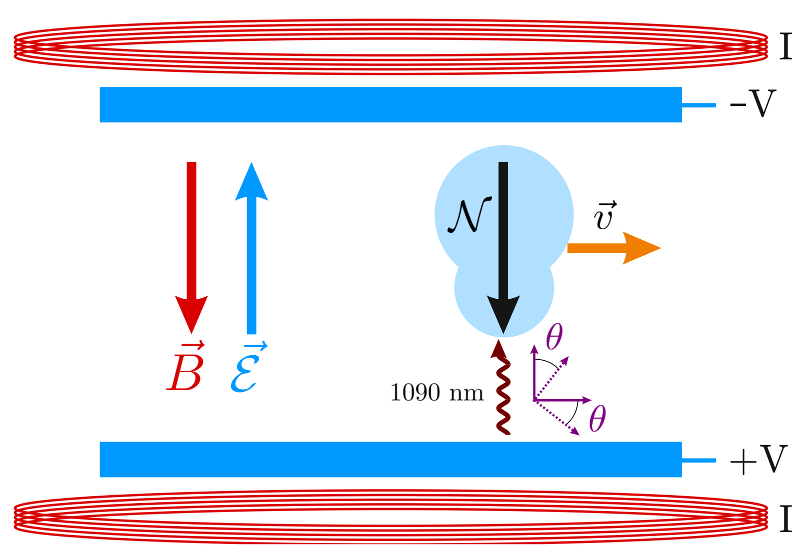
Three types of systematic error are included in our final error bar:

- Effects observed to shift the measured eEDM
- eEDM-like effects present in previous experiments
- Laser beam pointing associated effects

Below is a table of the included systematics in units of 10^{-29} e cm

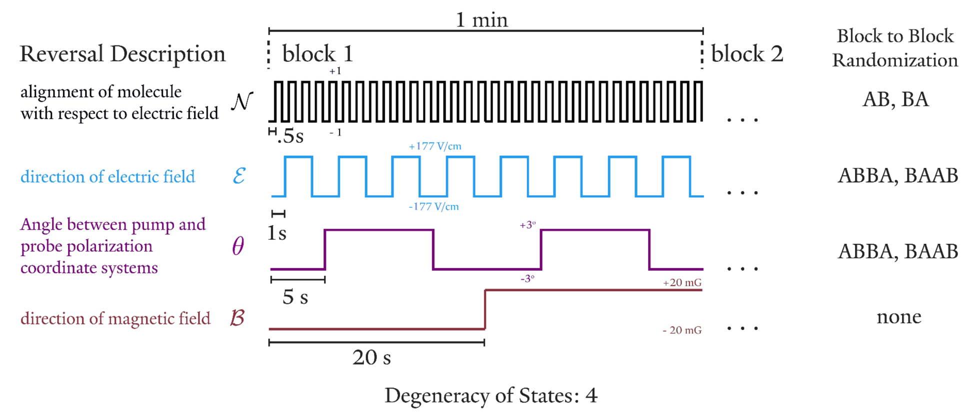
Parameter	Shift	Uncertainty
$\mathcal{E}^{nr}$ correction	−0.64	0.52
$\Omega_r^{\mathcal{N}\mathcal{E}}$ correction	−0.02	1.24
$\phi^{\mathcal{E}}$ correlated effects	−0.01	0.01
$\phi^{\mathcal{N}}$ correlation		0.98
Non-Reversing $\mathcal{B}$-field ($\mathcal{B}_z^{nr}$)		0.67
Transverse $\mathcal{B}$-fields $(\mathcal{B}_x^{nr}, \mathcal{B}_y^{nr})$		0.67
$\mathcal{B}$-Field Gradients		0.97
Prep./Read Laser Detunings		1.03
$\tilde{\mathcal{N}}$ Correlated Detuning		0.71
$\mathcal{E}$-field Ground Offset		0.13
Total Systematic	−0.67	2.54
Statistical		3.77
Total Uncertainty		4.54

Parameter Switches



In order to perform routine experimental diagnostics as well as rule out and suppress various sources of systematic errors in our measurement of the eEDM phase, we perform four main parameter switches as part of our experimental protocol.

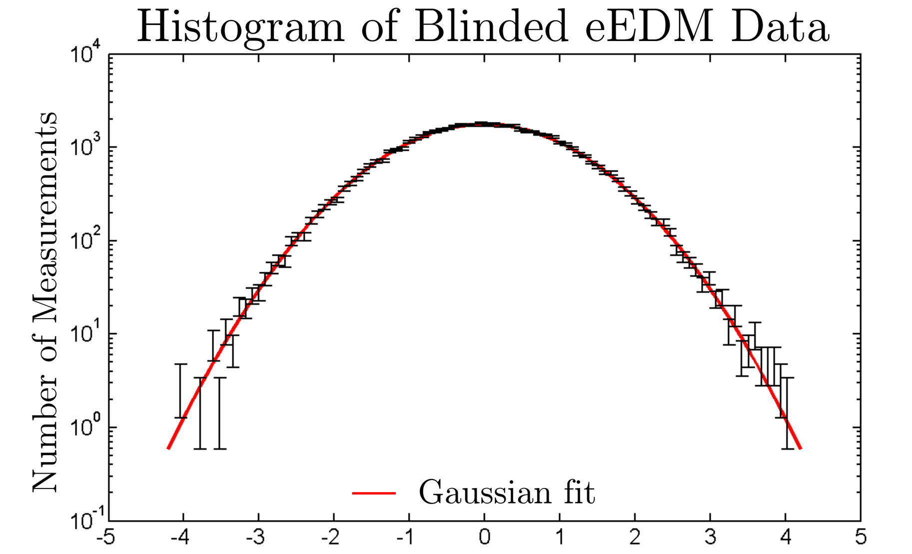
These switches are shown below in order of decreasing frequency:



Each block of data contains every permutation of these 4 switches.

A number of other switches are performed between blocks to aid the process of systematic error checking.

Statistics



T-Statistic of Blinded eEDM Measurements $\left(\frac{d_e - \langle d_e \rangle}{\sigma_{d_e}}\right)$

The above plot illustrates that our eEDM data is normally distributed to an excellent approximation.

The eEDM sensitivity that we achieve scales inversely with the square root of the integration time. Our large flux and large effective electric field both help give good sensitivity.

1-Day eEDM Statistical Uncertainty $\sim 1 \times 10^{-28}$ e · cm

References

For more information, visit **electronedm.info.**

ACME Papers

1. **Experimental Result:** "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron." ACME Collaboration. *ArXiv:1310.7534v2* (2013).
2. **Experiment proposal:** "Search for the electric dipole moment of the electron with thorium monoxide." A.C. Vutha et al. *Journal of Physics B* **43**, 074007 (2010).
3. **ThO buffer gas beam:** "A cryogenic beam of refractory, chemically reactive molecules with expansion cooling." N.R. Hutzler et al. *Phys. Chem. Chem. Phys.* **13**, 18976-18985 (2011).
4. **Dipole moments:** "Magnetic and electric dipole moments of the H state of ThO." A.C. Vutha et al. *PRA* **84**, 034052 (2011).
5. **Spin precession measurement:** "Shot-noise-limited spin measurements in a pulsed molecular beam." E. Kirilov et al. *ArXiv:1305.2179* (2013).
6. **Overview and update:** "Advanced cold molecule electron EDM." W.C. Campbell et al. *EJP*, to be published.

Other Papers: 7. **Previous eEDM limit:** J.J. Hudson et al. *Nature* **473** 493-496 (2011). 8. **Effective E-field of ThO:** E.L. Meyer and J.L. Bohn. *PRA* **78** 01052(R) (2008).