Order-of-magnitude improvement in the limit on the electron electric dipole moment

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Motivation & Theory
Permanent EDMs violate T-symmetry. Many theories beyond the Standard Model predict T violation and EDMs at current experimental precision.

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Data Acquisition Structure
The spin precession is performed under a variety of configurations of binary experimental variables, such as the electric and magnetic field directions, under which various terms in the Hamiltonian are odd or even. This enables us to study the components of the frequency that reverse under experimental switches by taking the difference of frequency measurements made with opposite values of the relevant switches. Through this we are also able to diagnose and suppress systematic effects.

By performing the experiment with different values of $\vec{N}$, $\vec{E}$, and $\vec{B}$ we can extract the EDM channel $\delta \vec{d}$, the component of the precession frequency which is odd under reversal of $\vec{N}$ and $\vec{E}$.

This measurement scheme results in robust suppression of systematic effects: any imperfections in the system would have to be correlated with both $\vec{N}$ and $\vec{E}$ to become a source of systematic error.

ACME II Apparatus

1. Buffer Gas Beam Source
2. Rotational Cooling
3. EDM State Preparation
4. Precession
5. State Readout

Magnetic Field Cooling

Contributions to the Systematic Uncertainty

Parameter | Uncertainty
---|---
Non-reversing Electric Field, $E^{\text{non}}$ | 0.36 $\sigma_{\text{stat}}$
$\vec{N}$ and $\vec{E}$ correlated contract variations, $|\delta \vec{N}^{\text{cor}}|, |\delta \vec{E}^{\text{cor}}|$ | 0.34 $\sigma_{\text{stat}}$
Magnetic field gradients, $\frac{\partial \vec{B}}{\partial z}$ | 0.16 $\sigma_{\text{stat}}$
STIRAP $\vec{N}$ correlated phase $\phi_{\text{STIRAP}}$ | 0.00 $\sigma_{\text{stat}}$
$\vec{E}$ correlated phases, $\psi$ | 0.00 $\sigma_{\text{stat}}$
Other magnetic field gradients | 0.36 $\sigma_{\text{stat}}$
$\vec{N}$ correlated variable phase power, $\gamma_{\text{STIRAP}}$ | 0.29 $\sigma_{\text{stat}}$
Non-reversing magnetic field, $\gamma_{\text{NR}}$ | 0.29 $\sigma_{\text{stat}}$
Transverse magnetic fields, $\gamma_{\text{trans}}$ | 0.25 $\sigma_{\text{stat}}$
Residuals | 0.20 $\sigma_{\text{stat}}$
Total | 0.82 $\sigma_{\text{stat}}$

These parameters showed no shift but a limit was included in the error bar.

Outlook
We have measured the electron EDM with a statistical uncertainty given by $\sigma_{\text{stat}} = 3.1 \times 10^{-29} e\text{cm}$ and the systematic uncertainties considered together give a smaller contribution. Our result provides a limit on the electron EDM that is an order of magnitude smaller than the best previous measurement, probing physics at energy scales of $\sim 3 - 30$ TeV.

Example Systematic 1: Correlation Between Prepared Phase and Laser Power

We discovered a nonzero dependence of $\delta \vec{d}$ on the laser power: $P_{\text{Laser}} = P_{\text{Laser}}^0 + \delta P_{\text{Laser}}$. The slope depended on the global polarization angle of the lasers. This dependence arose from a misalignment in the angle between the initial spin state (prepared by STIRAP) and the reference laser polarization. The reference laser not being perfectly attenuating the component of the spin perpendicular to its polarization, resulting in a shift in $\delta \vec{d}$ when $P_{\text{Laser}}$ is applied.

We are able to suppress this effect by both increasing the reference laser power and tuning the global polarization angle.

Example Systematic 2: Non-reversing Electric Field Gradients Coupling to Magnetic Field Gradients and Laser Detunings

1) Patch effects and voltage offsets can produce a gradient in the non-reversing electric field $E^{\text{non}}$.
2) This produces an $\vec{N}$ correlated detuning gradient, $\frac{\partial \vec{N}^{\text{cor}}}{\partial z}$.
3) Any detuning gradient couples to the efficiency $\eta$ of our state-preparation procedure (STIRAP) if we are not on resonance ($\delta \vec{N} \neq 0$).
4) The combination of $\frac{\partial \vec{N}^{\text{cor}}}{\partial z}$ and $\frac{\partial \vec{N}^{\text{cor}}}{\partial \psi}$ produces an $\vec{N}$ correlated shift in the beam center of mass along $z$, $\vec{d}^{\text{N}}$.
5) A magnetic field gradient $\gamma_{\text{M}}$ produces a spatially dependent precession frequency, which couples to the shift in center of mass to produce a shift in the EDM channel, $\delta \vec{d} = \frac{\partial \vec{N}^{\text{cor}}}{\partial \psi}$.

This systematic produces a shift in $\delta \vec{d}$ that is proportional to $\frac{\partial \vec{N}^{\text{cor}}}{\partial \psi}$.

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