SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF THE ELECTRON WITH THORIUM OXIDE

ACME collaboration

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Why measure the electron EDM?

EDM of a fundamental particle violates both parity (P) and time-reversal (T) symmetries:

\[ \varepsilon_I = (\mathbf{P} \mathbf{F}) \mathbf{I} \]

\[ \varepsilon_T = (\mathbf{T} \mathbf{F}) \mathbf{I} \]

\[ \varepsilon_{PT} = (\mathbf{P} \mathbf{T} \mathbf{F}) \mathbf{I} \]

T-violation in the Standard Model (SM) is not sufficient to explain the observed dominance of matter over antimatter in the universe → additional sources of T-violation (beyond the SM) must exist.

Additional T-violation in the lepton sector arises in most proposed extensions to the SM, while SM) must exist.

Optical pumping to A, which spontaneously decays to H, EDM of a fundamental particle violates both parity (P) and time-reversal (T) symmetries:

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The molecule can be almost completely polarized by applying a small electric field \( E_{\text{eff}} \).

Parity doublets in molecules

Electronic states with non-zero angular momentum (J ≠ 0) have parity doublets (J=±1).

Parity doublets arise due to the coupling of the electronic and rotational motion.

Energy separation between J=|±1| doublet components \( \Delta \Sigma = m_J \hbar \) = 10 MHz.

Advantages of ThO

- Optical pumping is a high flux, cryogenic beam.
- Suppressed magnetic moment in the H3 state → lower sensitivity to magnetic noise and systematics.

Cryogenic ThO beam

ThO is produced by laser ablation of solid ThO2 with a pulsed Nd:YAG laser (~10 mJ/pulse, 5 ns pulse).

THO molecules are cooled to 4 K by He buffer gas and entrained in the flow of He out of the cell (6 mm x 1 mm aperture, 10 sccm He flow [4 x 1018 atoms/sec]).

The ThO beam is detected via fluorescence on the X → C transition (typical signals are shown below). Measured beam flux is \( 1.5 \times 10^{12} \) molecules/s times a single quantum state. Measured beam divergence is \( \Delta x < 0.1 \mu \text{m} \).

EDM measurement with ThO

Optical pumping to A, which spontaneously decays to H, followed by depletion using x-polarized light on the H → C transition produces a coherent superposition of molecules in the J=1 rotational level of the H state: \( |0\rangle + |1\rangle + |2\rangle \).

After evolution in applied E and B-fields for time \( T \), the state is \( |J=1\rangle + |m=+1\rangle + |m=-1\rangle \), where \( f = \Delta E_{\text{mag}} + 2 \Delta E_{\text{Hor}} \). Evolution to the E state with y- or x-polarized light results in a coherent superposition of molecules in the J=1 rotational level of the H state produces a coherent superposition of molecules in the J=1 rotational level of the H state produces a coherent superposition of molecules in the J=1 rotational level of the H state produced.

Interaction region

- Transparent electric field plates (ITO-coated glass) under fabrication
- Interaction region vacuum chamber under fabrication
- Magnetic-shielding design and fabrication in progress

Laser systems and spectroscopy

- Lasers for state preparation and detection
- Digital locking system that can keep laser frequencies stable for >12hrs
- Measurements of dipole moment and g-factor for H state
- Demonstration of state preparation and detection of the accumulated phase

Current work

High flux beam source development

- Demonstrated production of atomic Yb beam with 4 K He buffer gas
- He beam studies started with Yb
- In progress

- Detailed beam studies and optimization
- Investigation of neon buffer gas
- Demonstration of high flux molecular beam

Energy shifts in J=1 level of H state

<table>
<thead>
<tr>
<th>Energy shift</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>( \Delta E_{\text{mag}} )</td>
<td>Magnetic moment ( \mu ) change</td>
</tr>
<tr>
<td>( \Delta E_{\text{Hor}} )</td>
<td>Electric field ( E_{\text{eff}} ) change</td>
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Statistical sensitivity:

\[ \delta_{\text{err}} = \frac{1}{2 \sqrt{N \tau}} \]

where \( N \) is the number of counts and \( \tau \) is the integration time.

H state lifetime

An exponential fit to the absorption data after the optical pumping pulse is turned off yields a lifetime of \( \tau = 1.8 \mu \text{s} \), which gives a lower bound on the H state radiative lifetime.

Optical pumping into H state

The plot at left shows absorption on the H → G transition with (orange) and without (blue) the presence of a pump beam tuned to the X → A transition.

The data shown here were taken in a buffer gas cell. We have also demonstrated optical pumping in a beam.

Acknowledgments

- I. Kozyryev, A. C. Vutha, D. DeMille
- W. C. Campbell

References

2. 4 K shield
30 cm from cell aperture,

Optical pumping to A

Use of both -doublet states enables demonstration of high flux molecular beam.

ThO can be made into a high-flux, cryogenic beam.

The large internal electric field rejection of systematic effects associated with reversal of the applied electric field.

Statistical sensitivity:

\[ \delta_{\text{err}} = \frac{1}{2 \sqrt{N \tau}} \]

where \( N \) is the number of counts and \( \tau \) is the integration time.

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