Towards a new measurement of the electron EDM with ThO:

Statistical improvements and systematic suppression

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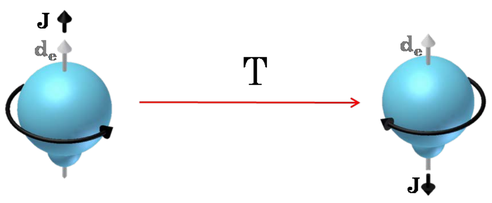
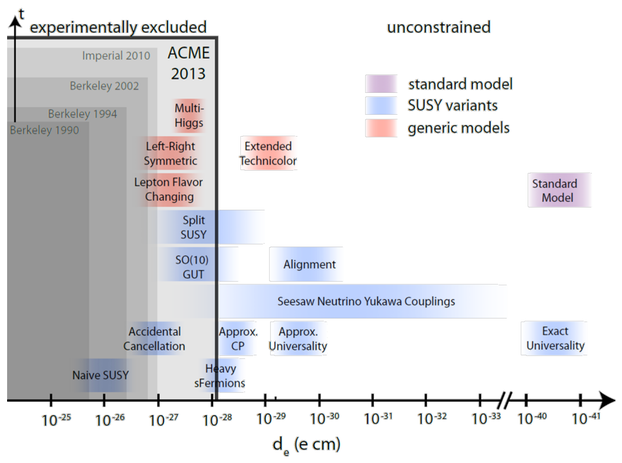
Abstract: Last year, the ACME collaboration set a new upper limit on the electron electric dipole moment (eEDM) of 10^{-28} e cm by means of a spin-precession measurement of a beam of thorium monoxide (ThO). This limit constrains many CP-violating theories beyond the Standard Model, and many of the theories that remain viable predict an eEDM within one or two orders of magnitude below this bound. To probe this regime, ACME is developing a second-generation experiment with a projected statistical sensitivity of 10^{-29} e cm in two weeks of averaging time. To this end, we are developing and testing (1) a new cryogenic buffer gas beam source of ThO that exploits a high-temperature chemical reaction between thorium and thorium dioxide, (2) geometric optimization of the molecular beam path and fluorescence collection, and (3) a coherent state-preparation scheme (STIRAP) for efficiently populating the eEDM state in ThO. Together, these improvements are projected to improve the sensitivity by a factor of at least 10. We will discuss these improvements in signal as well as steps we are taking to suppress sources of systematic error.

Motivation

- Permanent EDMs violate T-symmetry: a measurable eEDM would imply new T-violating interactions beyond the SM.
- New T-violating mechanisms are required for baryogenesis, i.e. an explanation of the universe's matter-antimatter asymmetry.





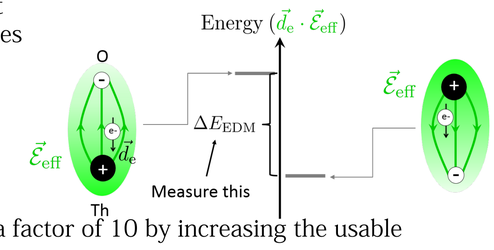
Measurement Scheme

- A permanent EDM of an electron orbiting close to the Th nucleus in ThO interacts with a huge (~80 GV/cm) effective electric field $\mathcal{E}_{\rm eff}$ generated by the highly-charged Th nucleus. The molecule is polarized with an applied E-field, orienting $\mathcal{E}_{\rm eff}$ in the lab frame.
- The electron spin precession phase is measured via the Ramsey method, and the total energy shift is deduced.
- The energy shift due to the EDM is isolated by repeating the measurement with a variety of parameter switches and keeping only the part that changes sign appropriately.
- The statistical uncertainty of the measurement is given by:

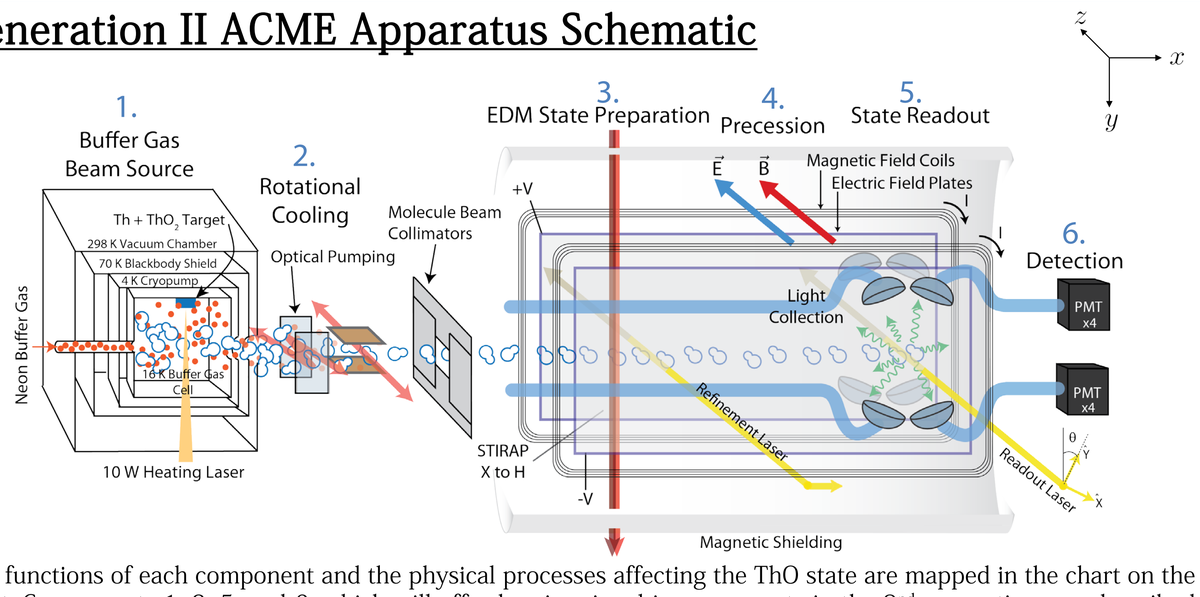
$$\delta d_e = \frac{\hbar}{2\mathcal{C}\tau\mathcal{E}_{\rm eff}\sqrt{\dot{n}T}}$$

τ = coherence time
$\dot{n}T$ = number of molecules
$\mathcal{E}_{\rm eff}$ = effective electric field

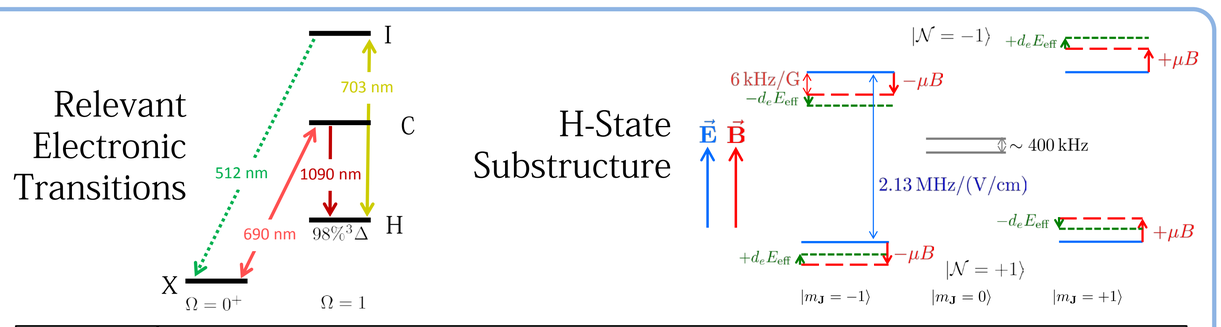
- 2nd generation improvements aim to reduce the statistical uncertainty by a factor of 10 by increasing the usable molecule flux by a factor of at least 100.



Generation II ACME Apparatus Schematic



The functions of each component and the physical processes affecting the ThO state are mapped in the chart on the right. Components 1, 3, 5, and 6, which will afford major signal improvements in the 2nd generation, are described in the following sections.



Region Function	1. Beam source		2. Rotational cooling	
ThO State	$\lvert X\rangle$	→	$\lvert X, J=0,1\rangle$	→ $\lvert X, J=0\rangle$
Process		Optical pumping via C		Optical pumping via C

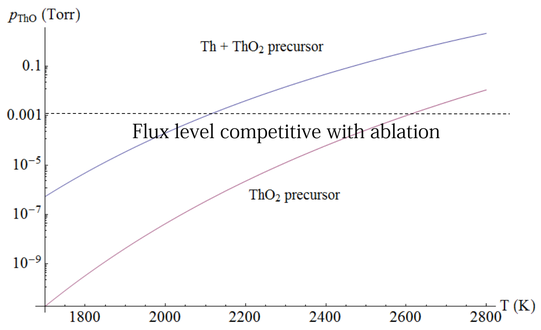
3. EDM state preparation	4. Interaction region	5. Readout
→ $\lvert H, J=1\rangle\, 1/\sqrt{2}(\lvert M=-1\rangle \pm \lvert M=+1\rangle)$	→ $1/\sqrt{2}(e^{-i\phi}\lvert M=-1\rangle \pm e^{i\phi}\lvert M=+1\rangle)$	→ $\lvert X\rangle$
STIRAP via C, refinement via H to I optical pumping	Phase precession	H to I optical pumping

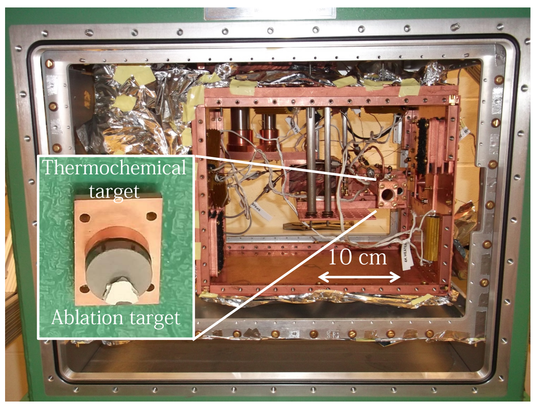
1. Thermochemical Beam Source

Relative to the ThO_2 ablation source used in the Generation I apparatus, we have demonstrated an order of magnitude improvement in the short-term time-averaged molecule flux via the high-T reaction: $ThO_2(s) + Th(s) \rightarrow 2ThO(g)$

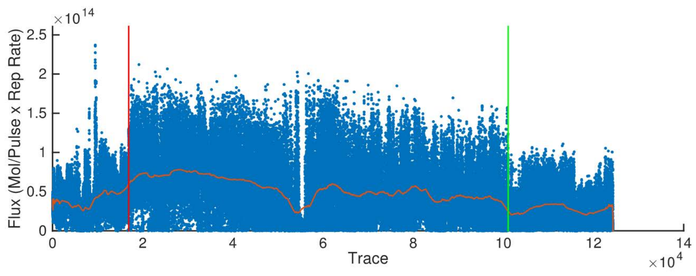
Favorable reaction rates are achieved in a pulse-tube-cooled cryogenic buffer gas beam apparatus by locally heating a Th + ThO_2 pressed powder precursor target via a focused, pulsed fiber laser. Significant challenges remain in improving the source longevity and controlling dust production.

Equilibrium partial pressure of ThO[4]





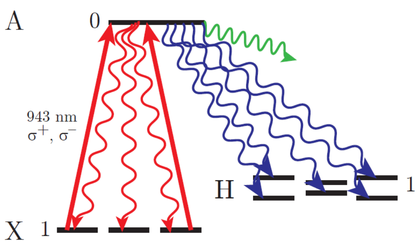
Generation II beam apparatus



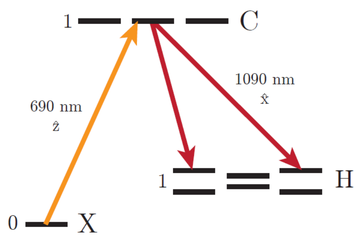
Preliminary data taken while running with 10 ms fiber laser pulses at 50 Hz with a typical peak power of about 20 W. Molecule flux demonstrated above is a factor of ~10 greater than in Generation I.

3. State Preparation

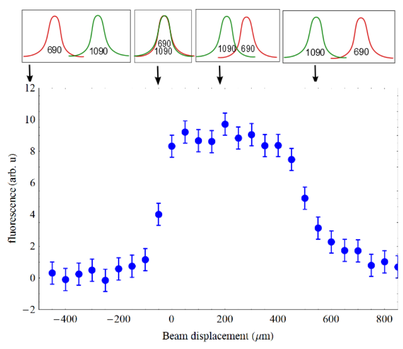
The EDM measurement is performed in the metastable H state. Replacing the original incoherent state preparation scheme with a coherent one is expected to improve our signal by up to a factor of 20.



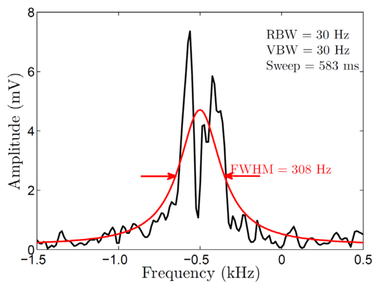
Generation I: Optical Pumping
Efficiency < 10%



Generation II : STIRAP
Projected efficiency >90%



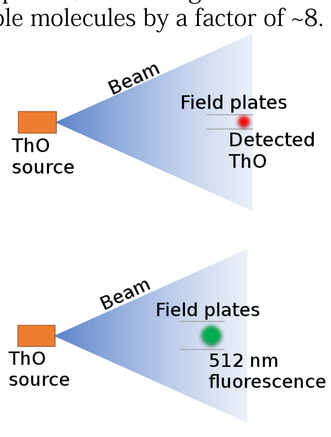
Lasers locked to homemade ULE cavities (above) exhibit ~100 Hz linewidths measured via a beat note (right).



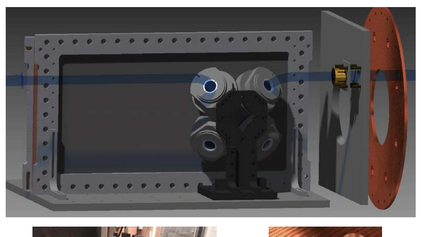
Preliminary tests have demonstrated a characteristic STIRAP signal (above) and an estimated factor of 4 improvement in population transfer efficiency relative to Generation I.

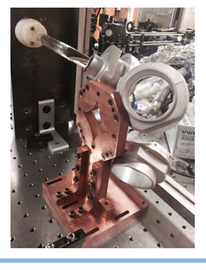
Detection Upgrades

Because of divergence, 99.99% of the molecules leaving the beam source do not reach the interaction region. Shortening the molecular beam line and increasing the distance between electric field plates allows a larger solid angle acceptance, increasing the flux of usable molecules by a factor of ~8.



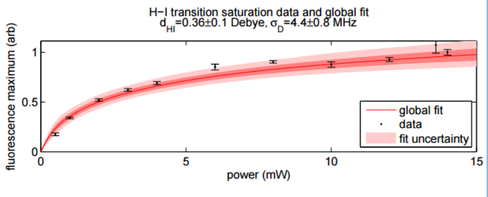
In addition, we have improved our collection optics for a factor of ~2 gain in detection efficiency. Bent light pipes will be used instead of fiber bundles to achieve higher packing fraction of detection area.



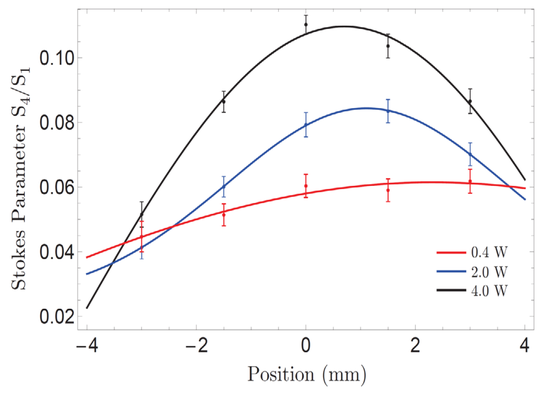


Detecting 512 nm fluorescence by optically pumping H state molecules through the I state suppresses the effect of scattered light from the 690 nm STIRAP laser. We have demonstrated saturation of this transition.

Higher detection efficiency at 512 nm results in a factor of ~2 signal increase relative to detecting 690 nm fluorescence from C to X as in Generation I.



Systematic Errors

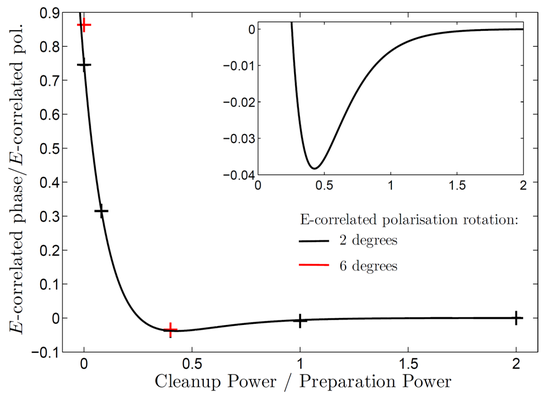


In Generation I, we identified a systematic effect caused by laser absorption in the field plates resulting in thermal stress-induced birefringence, which in turn imprinted an ellipticity gradient on the state preparation and readout laser polarizations (above).

New field plates with a lower thermal expansion and laser absorption and a higher thermal conductivity will suppress this effect by a factor of ~10.

We anticipate that polarization fluctuations in the state preparation STIRAP beams will lead to an EDM-like phase.

To account for this we plan on using an additional "refinement" laser beam to re-project the superposition state. Preliminary tests show this beam eliminates a systematic phase due to an electric-field-correlated polarization (below).



Conclusion

We aim to perform an improved measurement of the eEDM with a statistical uncertainty of 10^{-29} e cm. To this end, we have demonstrated significant signal gains relative to the first-generation experiment via thermochemical production of ThO, geometric improvements in the beam line and collection optics, and coherent state preparation. We have also recognized ways to mitigate known systematic effects. We are now developing, characterizing, and optimizing the final apparatus.

References

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More information: www.electronedm.info