Beyond the ACME II Limit on the Electron EDM

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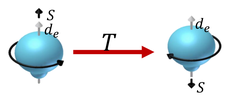
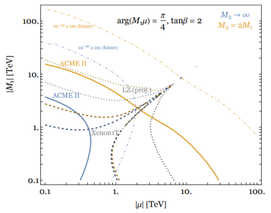
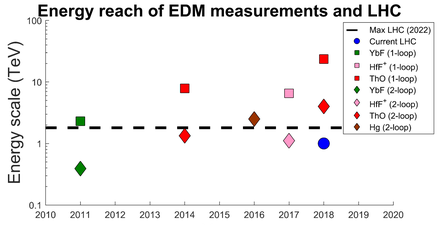
Motivation & Theory



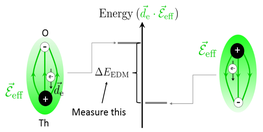
- Permanent EDMs violate *T*-symmetry.
- Many theories beyond the Standard Model predict *T* violation and EDMs at current experimental precision.



SUSY particle bounds from this result.
Fig. from Matt Reece (unpublished)
ACME III projection ($\sim 10^{-30} e \cdot cm$) dashed.



Key EDM results since 2010. Two-loop sensitivity from Nakai & Reece (2017).
One-loop sensitivity from Feng (2013). LHC scale gives stop mass sensitivity.

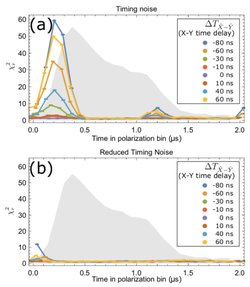


$$\delta d_e = \frac{\hbar}{2C\tau\mathcal{E}_{\rm eff}\sqrt{\dot{n}T}}$$

- ThO: effective electric field $E_{eff} \sim 80$ GV/cm
- ACME II parameters:
  - Precession time $\tau \sim 1$ ms
  - Measurement contrast $C \sim 0.95$
  - Detected molecule flux $\dot{n} \sim 1 \times 10^7\ s^{-1}$
  - Result: $d_e = (-4.3 \pm 4.0) \times 10^{-30}$ e · cm
  - $|d_e| < 1.1 \times 10^{-29}$ e · cm

Noise Reduction

- ACME II had **1.7 times more noise** than expected at the shot noise limit
- This noise was determined to come from both timing error in the data acquisition system and a timing offset between polarization bins
- **ACME III demonstrated improvement:** We were able to suppress this noise by controlling both parameters
- **ACME III planned improvement:** Reduce noise from velocity fluctuations by applying smaller magnetic fields
- **New magnetic shield designs** will need to reduce ambient fields to 1 μG and gradients to < 1 μG/cm

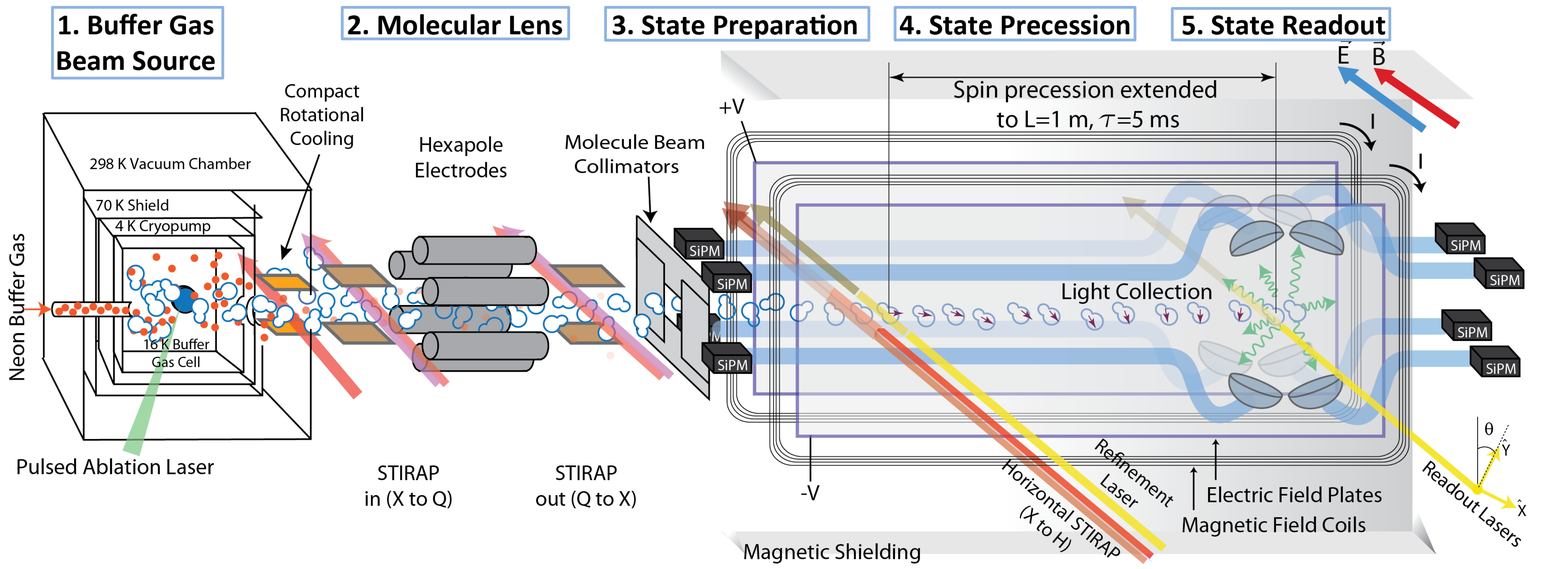


Systematic Search & Characterization

Parameter	Uncertainty ($10^{-30} e \cdot cm$)	
Non-reversing Electric Field, $\mathcal{E}^{nr}$	1.18	These parameters showed shifts in the EDM channel
$\tilde{N}\tilde{E}$ and $\tilde{N}\tilde{E}\tilde{B}$ correlated contrast variations, $\lvert\mathcal{C}\rvert^{\tilde{N}\tilde{E}}$, $\lvert\mathcal{C}\rvert^{\tilde{N}\tilde{E}\tilde{B}}$	1.05	
Magnetic field gradients, $\frac{\partial \mathcal{B}_z}{\partial z}$, $\frac{\partial \mathcal{B}_z}{\partial y}$	0.50	
STIRAP $\tilde{N}\tilde{E}$ correlated phase $\omega_{ST}^{\tilde{N}\tilde{E}}$	0.008	
$\tilde{E}$ correlated phases, $\phi^{\tilde{E}}$	0.008	
⋮	⋮	40 total parameters were varied during systematic checks
⋮	⋮	
Total Systematic	2.61	

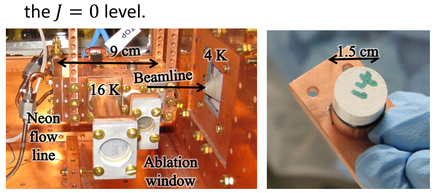
- In ACME II, **we varied 40 different experiment parameters** in the search for systematic errors (e.g. electric & magnetic fields, laser powers, detunings, pointing, polarization, molecular beam clipping, experiment timing, and analysis parameters)
- Where possible, we intentionally exaggerate the parameter and assume ω depends linearly on the parameter P. The systematic error under optimal conditions ($P = \bar{P}$) is given as
$$\omega_P^{\tilde{N}\tilde{E}} = \left(\partial\omega^{\tilde{N}\tilde{E}}/\partial P\right)\bar{P}$$
- The final contribution to the systematic uncertainty is computed from the linear error propagation of the two variables $\bar{P}$ and $\partial\omega^{\tilde{N}\tilde{E}}/\partial P$.
- **ACME III planned improvement:** further suppress systematics related to E^{nr} using **improved electric field plates** and **horizontal STIRAP**

ACME III Apparatus

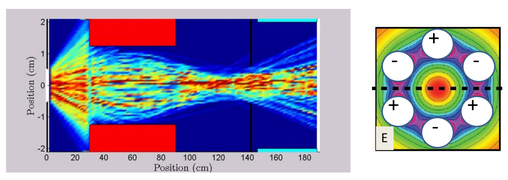


1. Buffer Gas Beam Source

- Produce ThO molecules through **pulsed ablation of a ceramic ThO_2 target** at 50 Hz
- Neon buffer gas thermalizes the molecules. Molecule beam is cooled to 4 K
- ~10^{11} molecules/sr in the electro-vibrational ground state.
- Rotational cooling transfers more population to the $J = 0$ level.



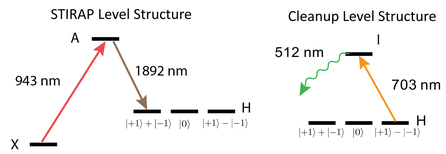
2. Molecular Lens



- **ACME III planned improvement:** Improve collimation of molecular beam by applying a hexapole electric field
- Requires compact rotational cooling to maximize input flux
- Molecules are transferred efficiently from the ground state (X) to the lensing state Q and back using X-C-Q STIRAP
- Demonstrated double **STIRAP efficiency >75%**
- Expected increase of molecular flux by a factor of 15 vs. ACME II

3. State Preparation

- STIRAP **coherently transfers population** to experimental H-state with ~75% efficiency (ACME II)
- **ACME III planned improvement:** perform **STIRAP horizontally** through the X-A-H states (1892 nm, 943 nm), which will allow better suppression of systematics caused by birefringence gradients
- 703 nm cleanup laser reprojects the state onto a coherent superposition of $M = +1, M = -1$ states



4. State Precession

- The molecules in the prepared state **acquire phase** as they fly through the electric and magnetic fields of the interaction region.

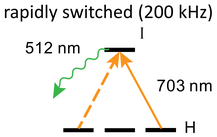
$$\frac{1}{\sqrt{2}}(|-1\rangle + |+1\rangle) \longrightarrow \frac{1}{\sqrt{2}}(e^{i\phi}|-1\rangle + e^{-i\phi}|+1\rangle)$$

$$\frac{\phi}{\tau} = -(\tilde{\mathcal{B}} g_1 \mu_B \mathcal{B}_z + \tilde{\mathcal{N}}\tilde{\mathcal{E}} d_e \mathcal{E}_{eff})$$

- **ACME III planned improvement:** Recent measurements determined that the lifetime of the H-state is 4-6 ms, allowing us to **increase precession time by a factor of 4-6** compared to ACME II (improved lifetime measurements are underway)
- Increased precession time decreases solid angle that reaches the detection region (see table below)
- Molecular lens will help to counteract this loss
- Requires new interaction region design to accommodate increased length

5. State Readout

- After precession, the final state is **projected to a pair of orthogonal basis vectors** using a 703 nm probe laser (on the H-I transition) with linear polarization rapidly switched (200 kHz) between x and y.



- We **collect the 512 nm fluorescence** as the molecules decay back to the ground state.
- **ACME III planned improvement:** upgrade PMTs to **silicon photomultipliers (SiPMs)** and optimize collection optics
- SiPM characterization tests have been performed

	Requirement	Measured Value
Photon Detection Efficiency	~ 50%	2.5 x PMT
Dark Count Rate	< 10 Mcps	< 10 Mcps @ -10 °C
Cross Talk and After Pulse	< 25%	~ 15%

Overall projected sensitivity

Improvement	Signal Gain	EDM Sensitivity Gain
Increased precession time	0.20	2.3
Electrostatic lens	20.5	4.5
SiPM detector upgrade	2.3	1.5
Timing jitter noise reduction*	1	1.7
Total	**9.4**	**26.4**
ACME II daily statistical sensitivity		$\sim 1 \times 10^{-29} e \cdot cm$
Projected ACME III daily sensitivity		$\sim 4 \times 10^{-31} e \cdot cm$

*Already implemented

References

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Interpreting the Electron EDM Constraint: C. Cesarotti et al., *J. High Energ. Phys.* **2019**:59 (2019)