Progress Towards the ACME III Search for the Electron Electric Dipole Moment

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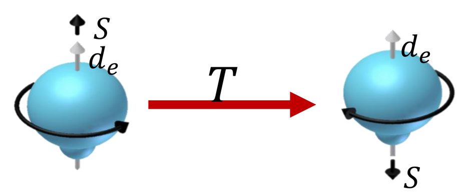
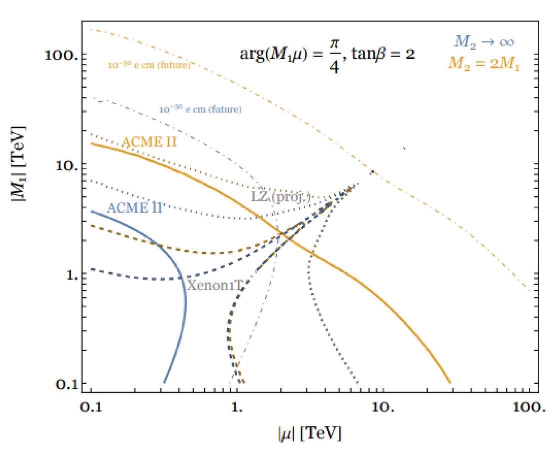
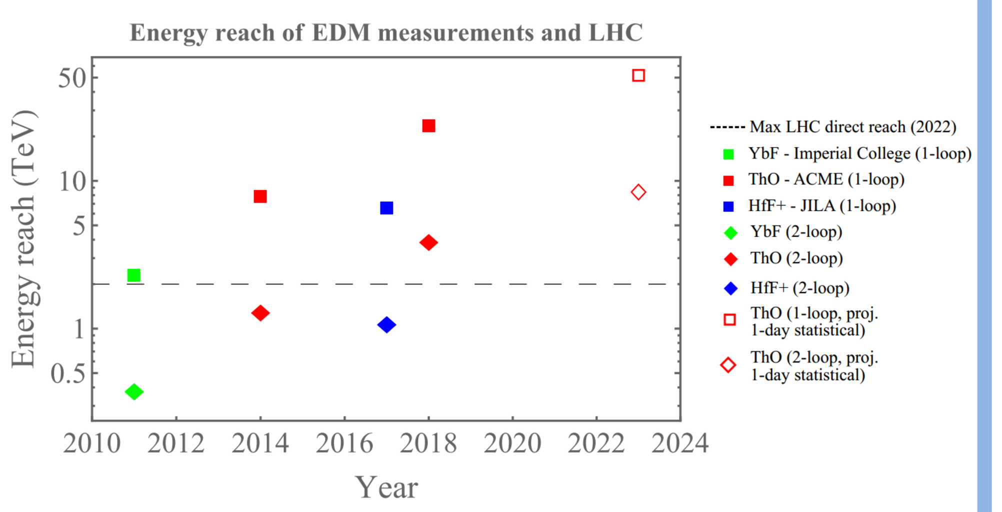
Motivation & Theory



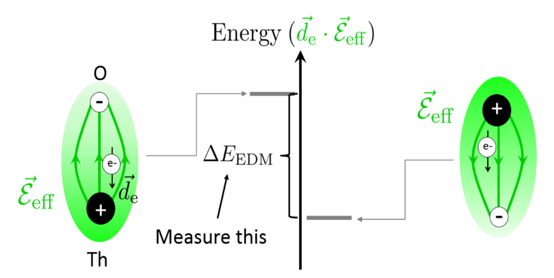
- Permanent EDMs violate *T*-symmetry.
- Many theories beyond the Standard Model predict *T* violation and EDMs at current experimental precision.



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 from Matt Reece (unpublished)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.

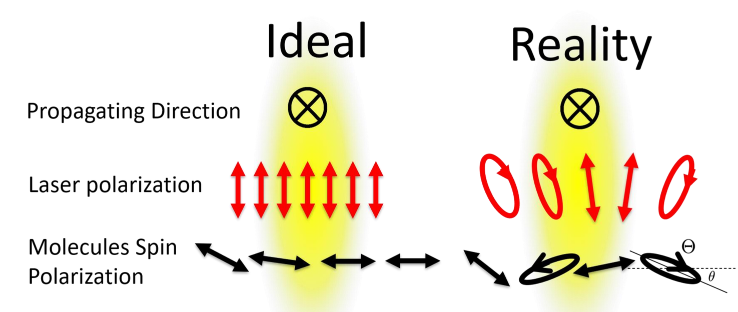


$$\delta d_e = \frac{\hbar}{2C\tau \mathcal{E}_{eff}\sqrt{\dot{n}T}}$$

- 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

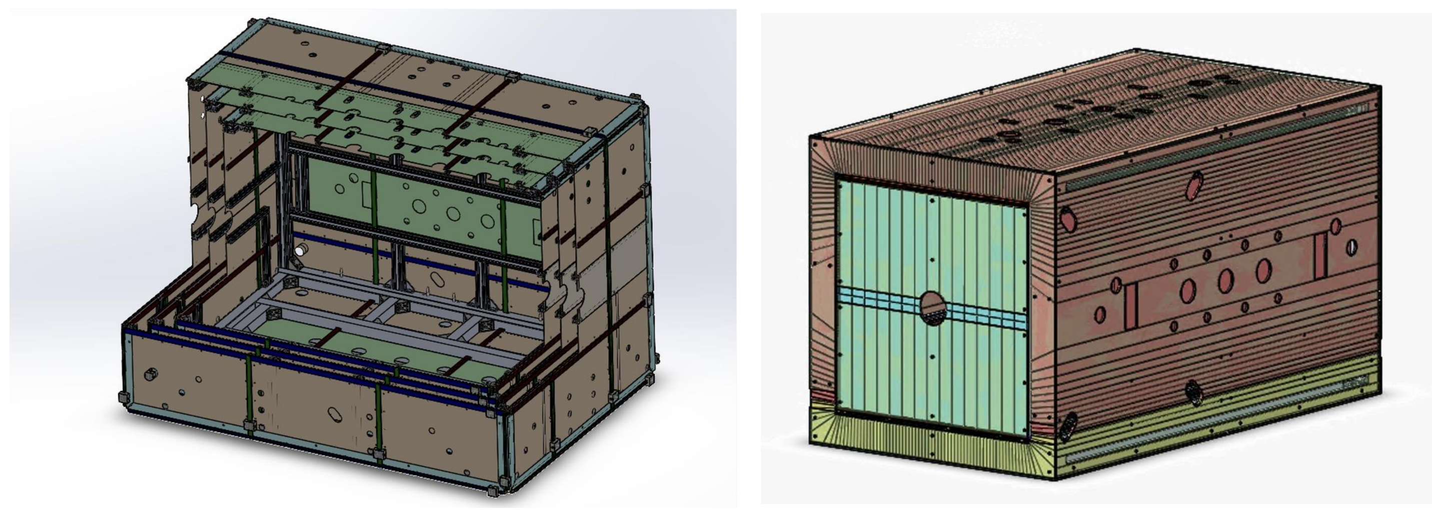
Systematic Error Suppression

- The largest source of systematic uncertainty in ACME II came from non-reversing electric fields
- Non-reversing electric fields couple to the EDM value through **imperfect polarization** of the cleanup and readout lasers
- **ACME III planned improvement:** Produce new transparent field plates with **improved optical properties to reduce polarization imperfections**, that have flat, parallel, and smooth surfaces.
- Use SF57HTUltra glass to reduce the stress-optic coefficient by **~40x** versus ACME II
- Field plates must also be increased in size to match the increased 1m precession length, requiring composite field plates
- For more information see poster **N01.00100**



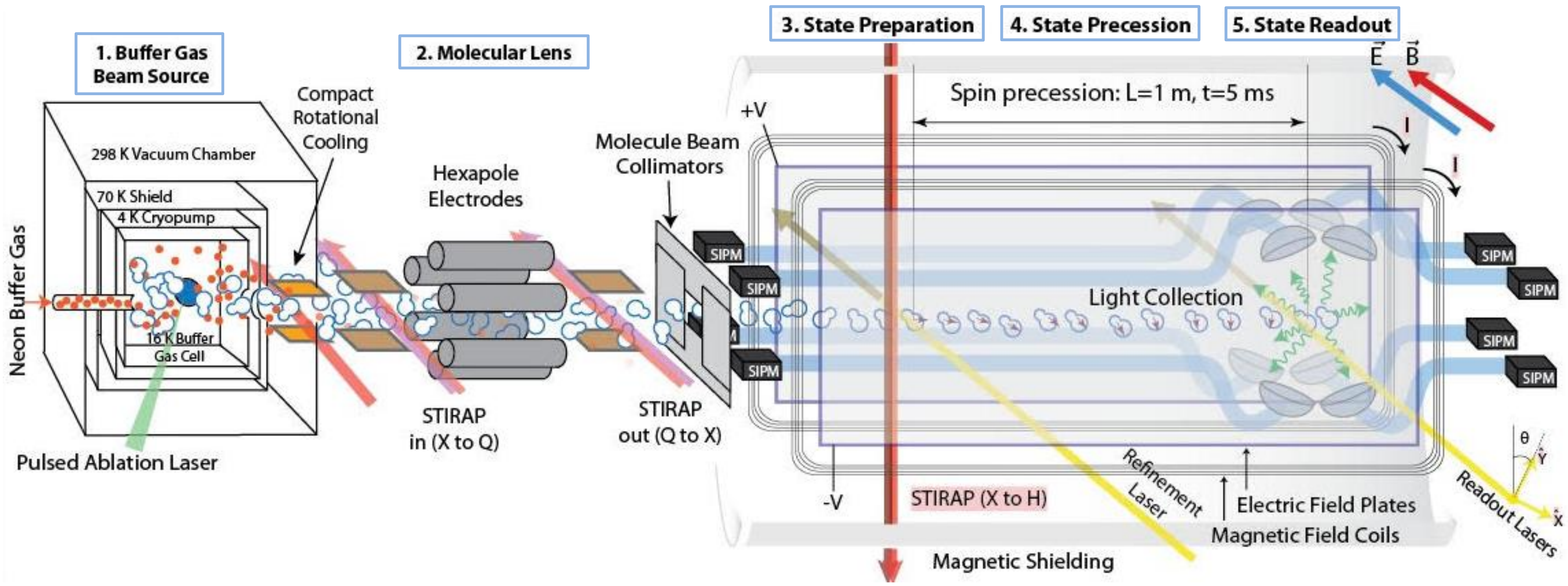
Noise Reduction

- ACME II had **1.7 times more noise** than expected at the shot noise limit
- Excess noise came from both a 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 II also saw excess noise when running with large (~10 mG) applied magnetic fields, caused by fluctuations in the molecular beam velocity
- **ACME III planned improvement:** Reduce noise from velocity fluctuations by applying smaller magnetic fields
- **New 3-layer magnetic shields** will need to reduce ambient fields to 1 μG and gradients to < 1 μG/cm
- A **self-shielded cosine theta coil** will allow us to apply uniform fields in the interaction region, while keeping fringe fields at the shields below 5 μG
- For more information see poster **F01.00004**



Designs for the 3-layer mu metal magnetic shields (left), and the self shielding cosine theta and gradient coils (right).

ACME III Apparatus



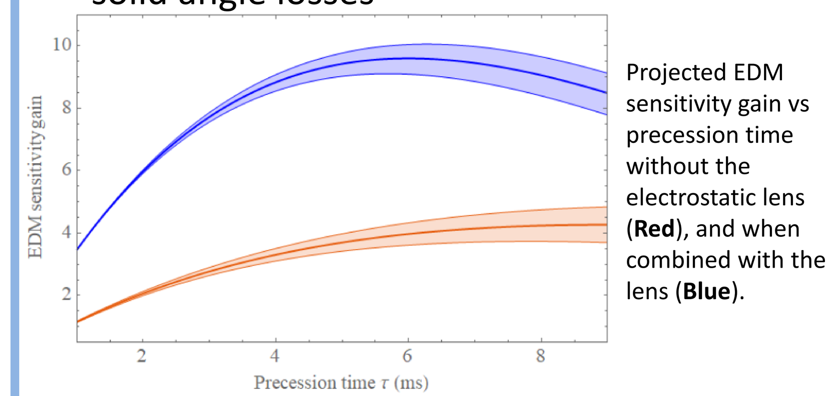
4. State Precession

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

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

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

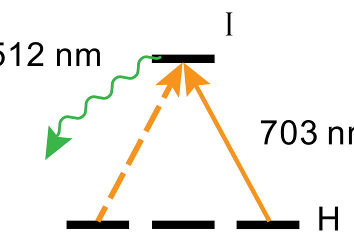
- Recent measurements determined that the lifetime of the H-state is **4.6 ms**
- For more information see talk **K03.00001**
- **ACME III planned improvement:** Develop new apparatus to **increase precession time by a factor of 5** compared to ACME II
- Electrostatic lens helps compensate for solid angle losses



Projected EDM sensitivity gain vs precession time without the electrostatic lens (**Red**), and when combined with the lens (**Blue**).

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.

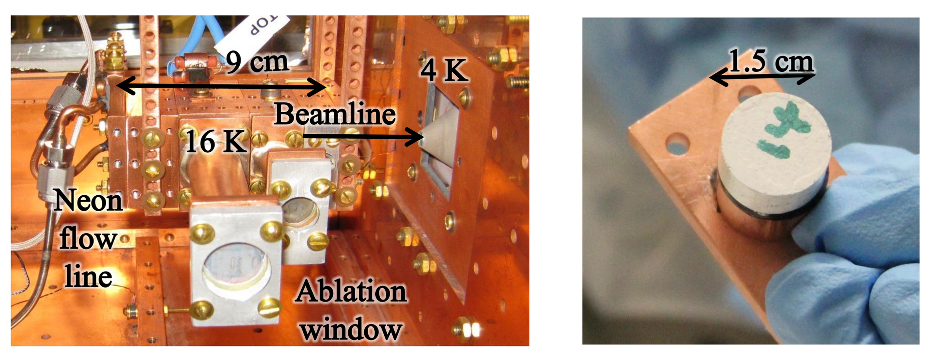


- We **collect the 512 nm fluorescence** as the molecules decay back to the ground state.
- **ACME III planned improvement:** upgrade PMTs to **silicon photomultipliers (SiPMs)** and optimize collection optics
- SiPM characterization tests have been performed
- For more information see poster **N01.00095**

	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%

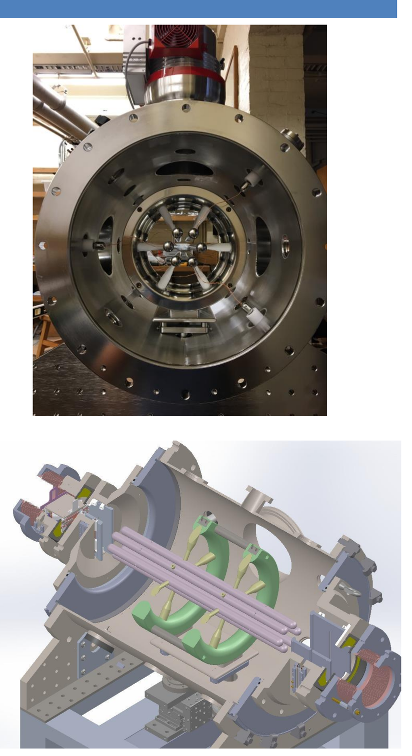
1. Buffer Gas Beam Source

- Produce ThO molecules through **pulsed ablation of a ceramic ThO_2 target** at 50 Hz
- Neon buffer gas thermalizes the molecules at 16K, beam expansion cools to 4K
- ~10^{11} molecules/sr in the vibronic ground state
- **ACME III demonstrated improvement:** a new compact rotational cooling scheme has been demonstrated, reaching up to a factor of 3.6 signal gain



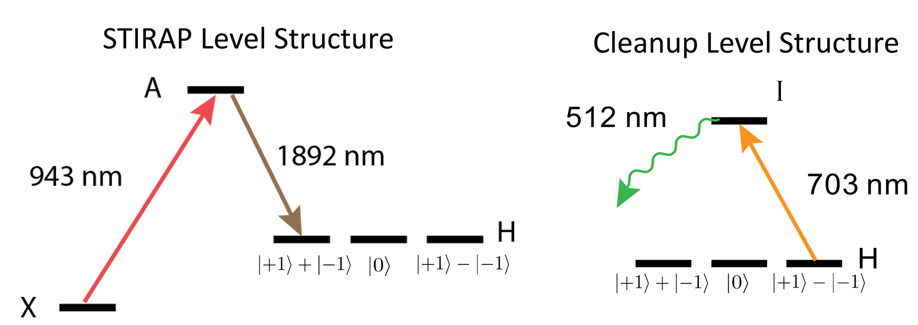
2. Molecular Lens

- **ACME III planned improvement:** improve molecular beam flux by focusing with a hexapole electrostatic lens
- The highly polarizable Q state of ThO allows the electric lens to enhance the EDM signal by about 20 times when turned on, based on trajectory simulation
- **First signal** at Lens exit shows a factor of **2.5 signal gain**, consistent with prediction from trajectory simulations
- **Demonstrated efficient STIRAP** transfer into and out of the Q state, with about **80% total efficiency**
- For more information see: **K03.00002**



3. State Preparation

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



Overall projected sensitivity

Improvement	Signal Gain	EDM Sensitivity Gain
Increased precession time		5
Electrostatic lens	9.6	3.1
SiPM detector upgrade	2.3	1.5
Improved Collection Optics	1.5	1.2
Increased decay time	0.45	0.67
Timing jitter noise reduction	1	1.7
Total	**14.9**	**31.8**
ACME II daily statistical sensitivity		$\sim 1 \times 10^{-29} e \cdot cm$
Projected ACME III daily sensitivity		$\sim 3 \times 10^{-31} e \cdot cm$

References

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ACME I result: J Baron et al., *Science* **343**, 269-272 (2014)
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E_{eff} Calculations: L. V. Skripnikov et al., *J. Chem. Phys.* **142** 024301 (2015), T. Fleig et al., *J. Mol. Spec.* **300:**16-21 (2014)
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Interpreting the Electron EDM Constraint: C. Cesarotti et al., *J. High Energ. Phys.* **2019**:59 (2019)