Search for the electric dipole moment of the electron with thorium oxide

ACME collaboration

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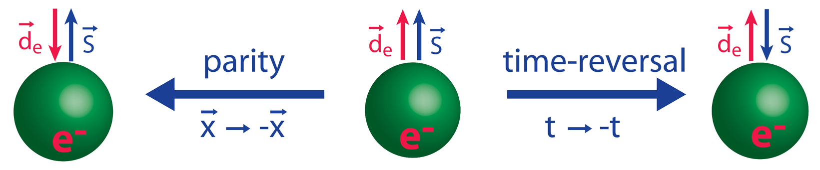
Why measure the electron EDM?

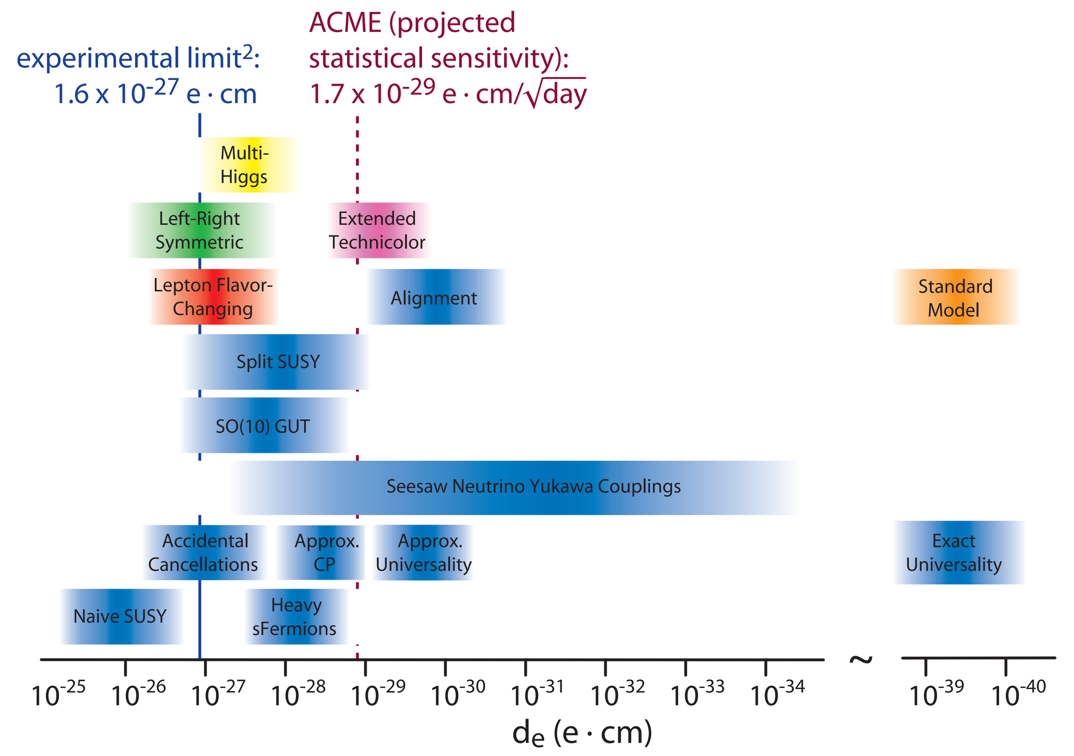
EDM of a fundamental particle violates both parity (P) and time-reversal (T) symmetries:



T-violation in the Standard Model (SM) is not sufficient to explain the observed dominance of matter over antimatter in the universe $\Longrightarrow$ 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, which generically predict $d_e \gtrsim 10^{-29}$ e · cm. An experimental limit on d_e below ~10^{-29} e · cm would also put strong constraints on possible mechanisms of electroweak baryogenesis[1].

Predictions for the electron EDM from the SM and some proposed extensions:



[1] Y. Li, S. Profumo, and M. Ramsey-Musolf, arXiv:0811.1987v1 [hep-ph].
[2] B. C. Regan *et. al.*, Phys. Rev. Lett. **88**, 071805 (2002).

Advantages of ThO

Advantages for statistical sensitivity

The effect of an electron EDM is amplified in a polar molecule like ThO due to the large internal electric field E_{eff} of the molecule. For ThO in the H state, $E_{eff} = 104$ GV/cm.[3]

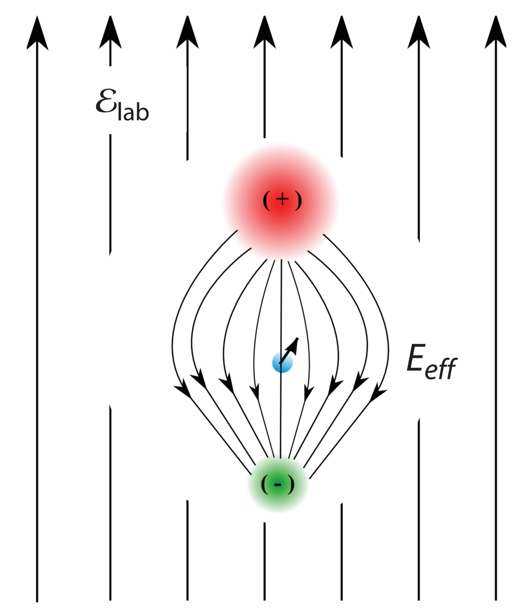
ThO can be made into a high-flux, cryogenic beam.

Properties that reduce systematic effects

The molecule can be almost completely polarized by applying a small electric field $\mathcal{E}_{lab} \sim 10$ V/cm. Smaller applied field $\Longrightarrow$ smaller leakage currents.

Ω-doublet in H state of ThO $\Longrightarrow$ two closely spaced, opposite-parity states with equal and opposite values of E_{eff}. Use of both Ω-doublet states enables rejection of systematic effects associated with reversal of the applied electric field.

Suppressed magnetic moment in the $H^3\Delta_1$ state $\Longrightarrow$ lower sensitivity to magnetic noise and systematics.



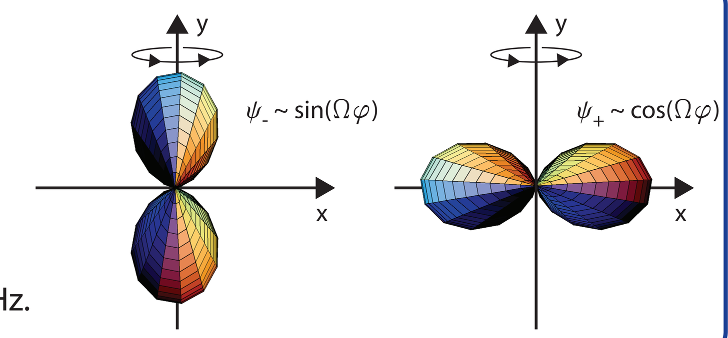
[3] E. R. Meyer and J. L. Bohn, Phys. Rev. A **78**, 010502 (2008).

Parity doublets in molecules

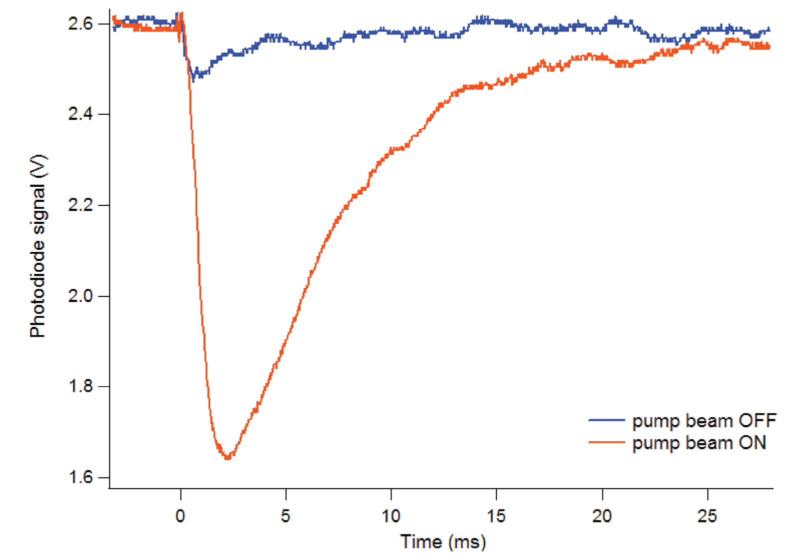
Electronic states with non-zero angular momentum ($\Omega \neq 0$) have parity doublets (Ω-doublets).

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

Energy separation between Ω-doublet components $\Delta E \sim \frac{m_e}{M_n} B_e \simeq 10$ MHz.



Optical pumping into H state

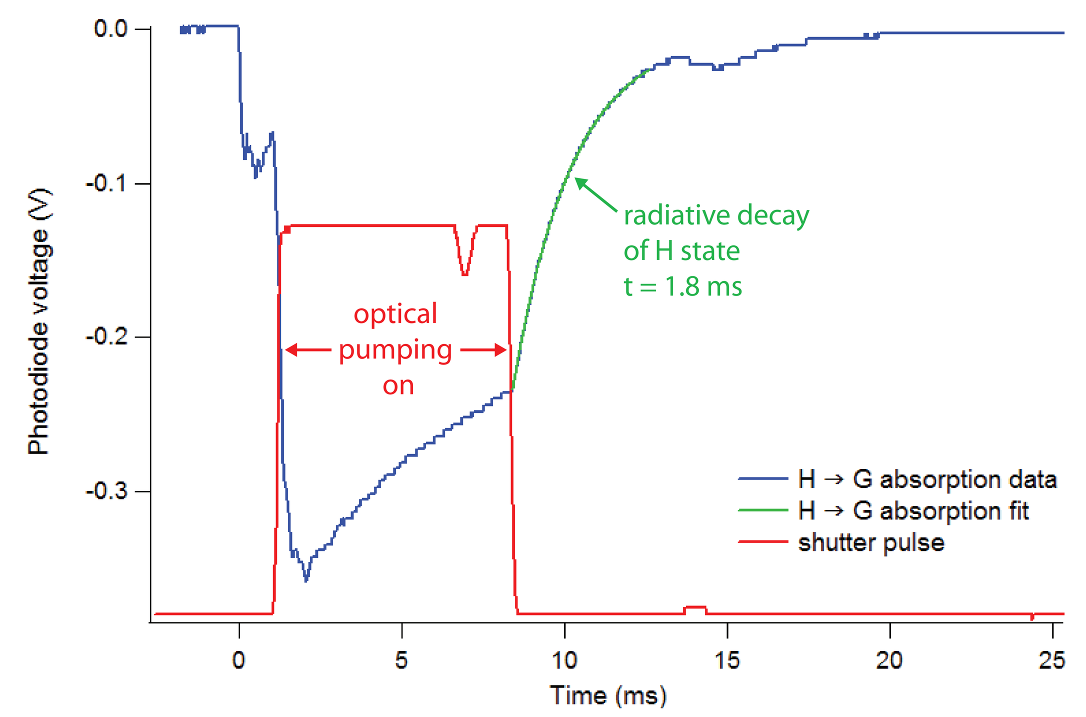


The plot at left shows absorption on the H → G transition with (orange) and without (blue) the presence of a pump beam tuned to the X → A transition.

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

H state lifetime

An exponential fit to the absorption data after the optical pumping pulse is turned off yields a lifetime of $\tau = 1.8$ ms, which gives a lower bound on the H state radiative lifetime.

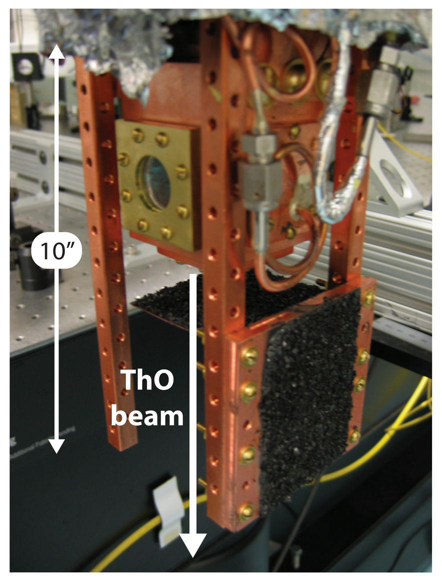


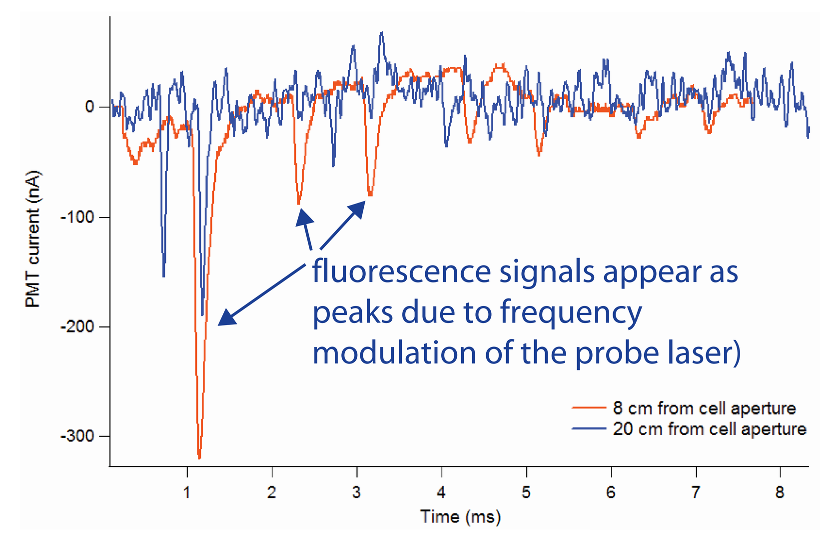
Cryogenic ThO beam

ThO is produced by laser ablation of solid ThO_2 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 (6mm x 1mm aperture, 10 sccm He flow [4×10^{18} atoms/sec]).

The ThO beam is detected via fluorescence on the X → C transition (typical signals are shown below). Measured beam flux is ~1.5×10^{10} molecules/shot in a single quantum state. Measured beam divergence is $\Omega_b < 0.1$ sr.

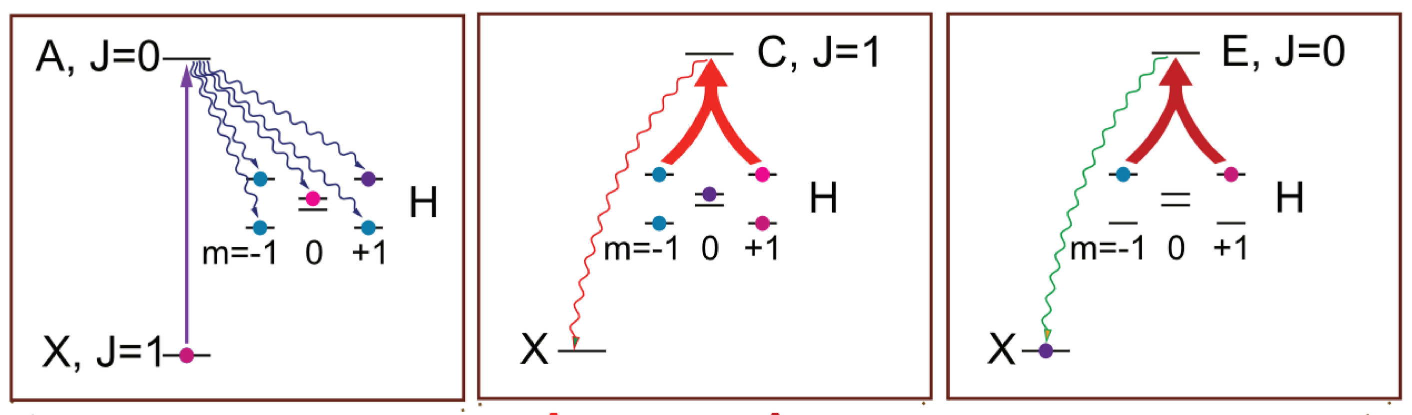


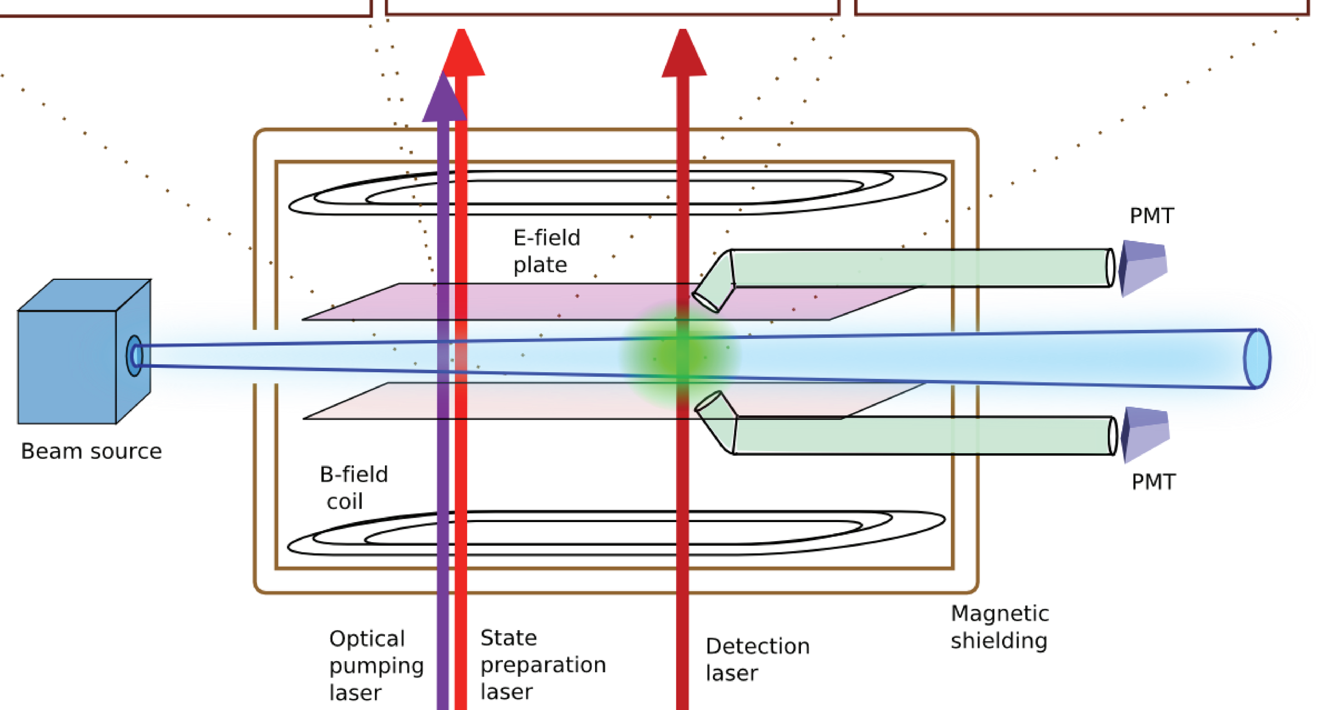


EDM measurement with ThO

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: $|\psi(0)\rangle = |m{=}{+}1\rangle + |m{=}{-}1\rangle$.

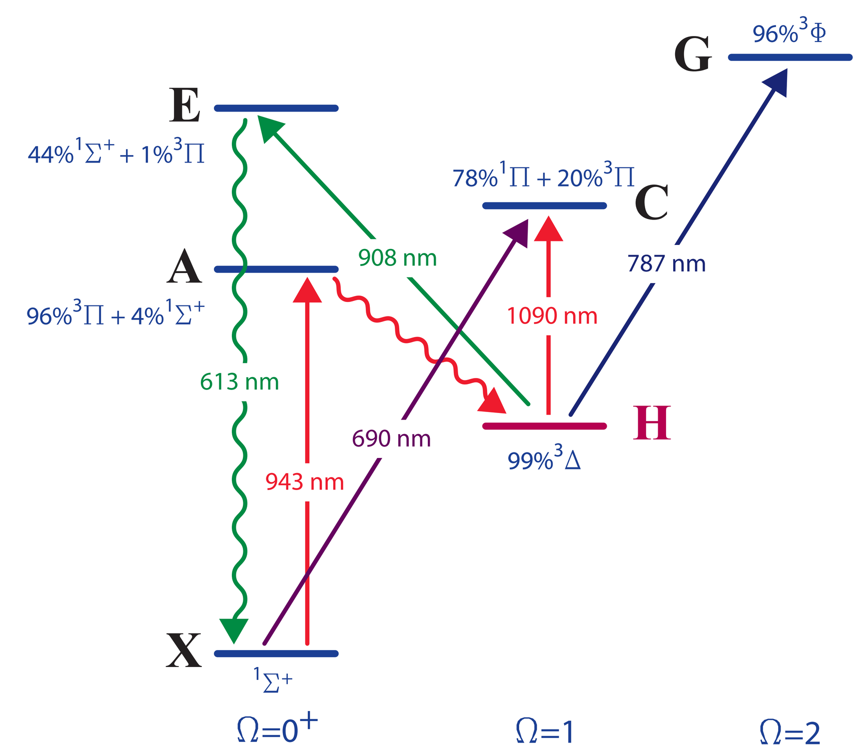
After evolution in applied $\mathcal{E}$- and B-fields for time T, the state is $|\psi(T)\rangle = |m{=}{+}1\rangle + e^{i\phi}|m{=}{-}1\rangle$, where $f = (2g\mu_B B \pm 2d_e E_{eff})T/\hbar$. Excitation to the E state with y- or x-polarized light results in a population in E that depends on φ: $P_E \propto 1 \pm \cos\varphi$.



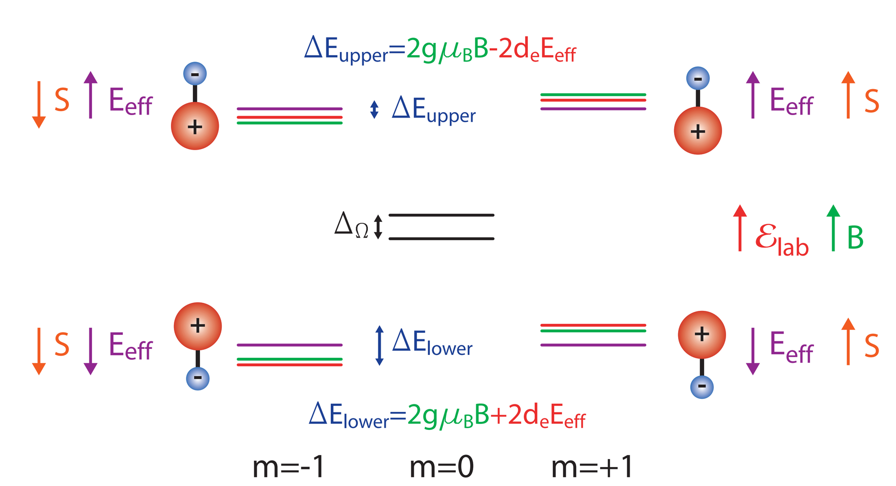


Statistical sensitivity: $\delta d_e = \frac{1}{2E_{eff}} \frac{\hbar}{\tau\sqrt{\dot{N}T}}$

internal electric field — coherence time — counting rate — integration time



Energy shifts in J=1 level of H state

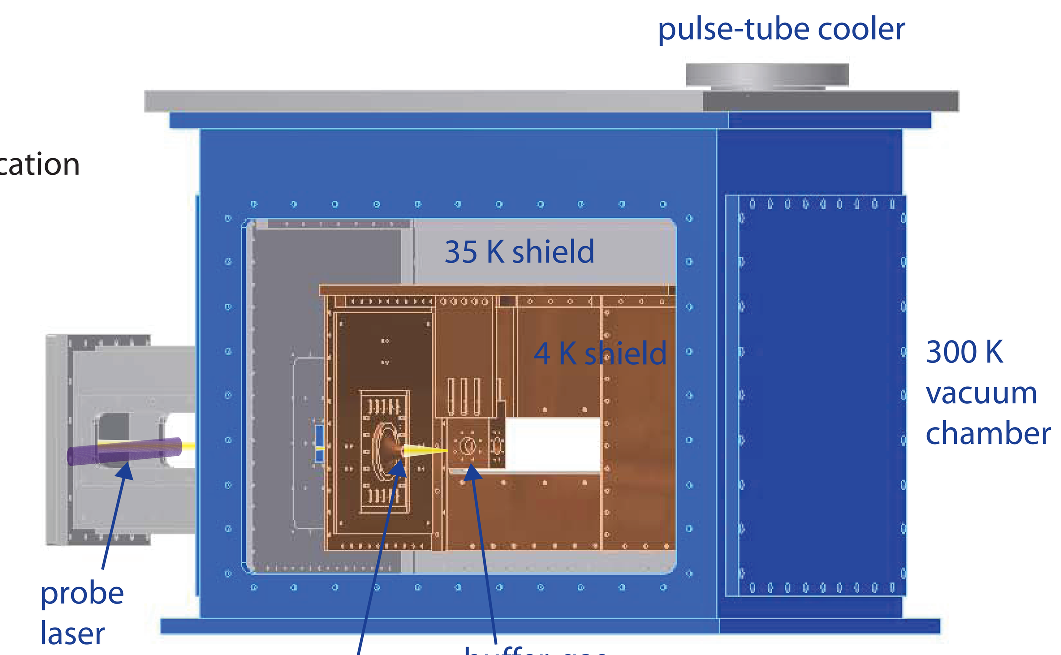


Current work

High flux beam source development

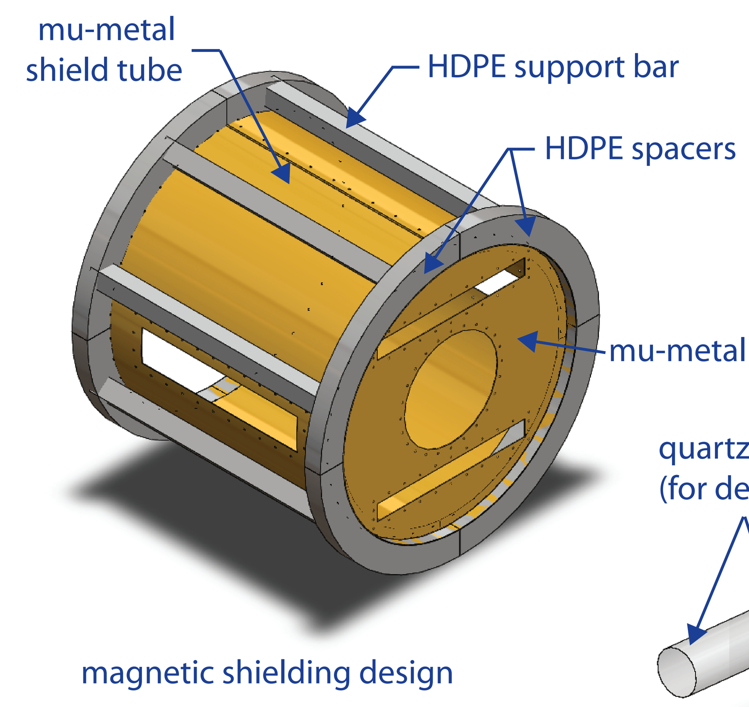
- ☑ Demonstrated production of atomic Yb beam with 4 K He buffer gas
- ☑ He beam studies started with Yb
- ☐ In progress
  - Detailed beam studies and optimization
  - Investigation of neon buffer gas[4]
  - Demonstration of high flux molecular beam

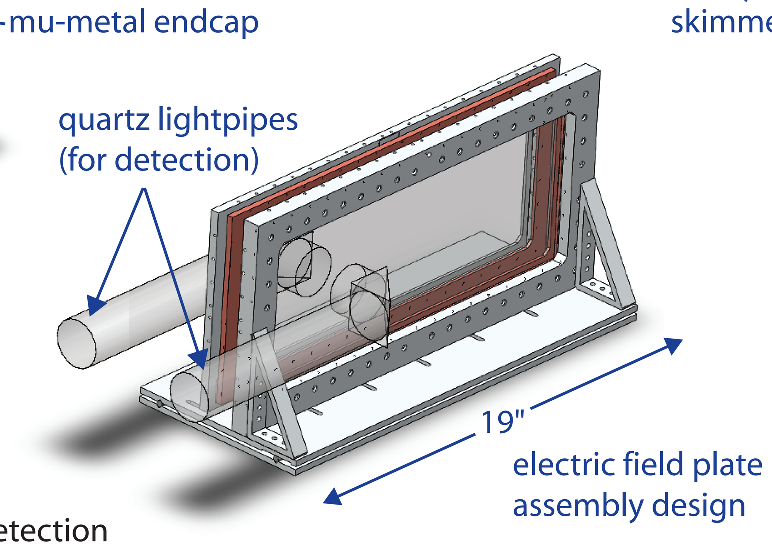
[4] D. Patterson, J. Rasmussen, and J. M. Doyle, arXiv:0812.2212 [physics.atom-ph].

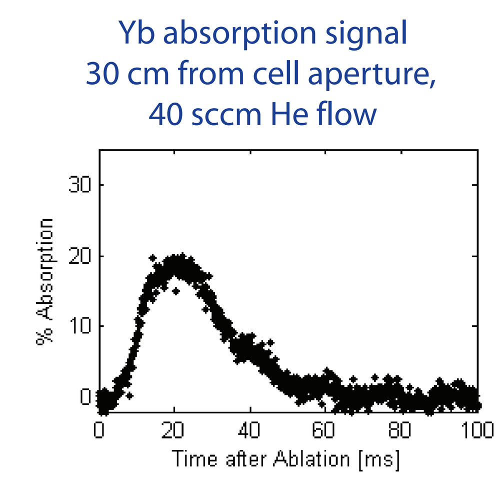


Interaction region

- ☑ 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