Experiment to search for electron electric dipole moment using laser cooled Cs atoms

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Introduction

- We describe our apparatus, which is designed to be sensitive to an electron EDM as small as 10^{-29} *e·cm*.
- Our measurement should be much more sensitive than previous measurements, because atoms can be stored in the trap for tens of seconds, allowing for much narrower Zeeman resonance linewidths.
- Our method will eliminate the most important systematic errors, proportional to atomic velocity, which have limited previous experiments.
- An important feature of our apparatus is that magnetic field gradient noise will be suppressed to a very low value of the order of a $fT/\,cm\,Hz^{1/2}$.

Motivation of EDM experiments

- An electron can possess an electric dipole moment (edm) only if time reversal symmetry (T) is violated
- By the CPT theorem, T violation is equivalent to CP violation.
- CP is violated in the standard model (e.g. in Kaon decay), but this leads to edms far too small to observe experimentally.

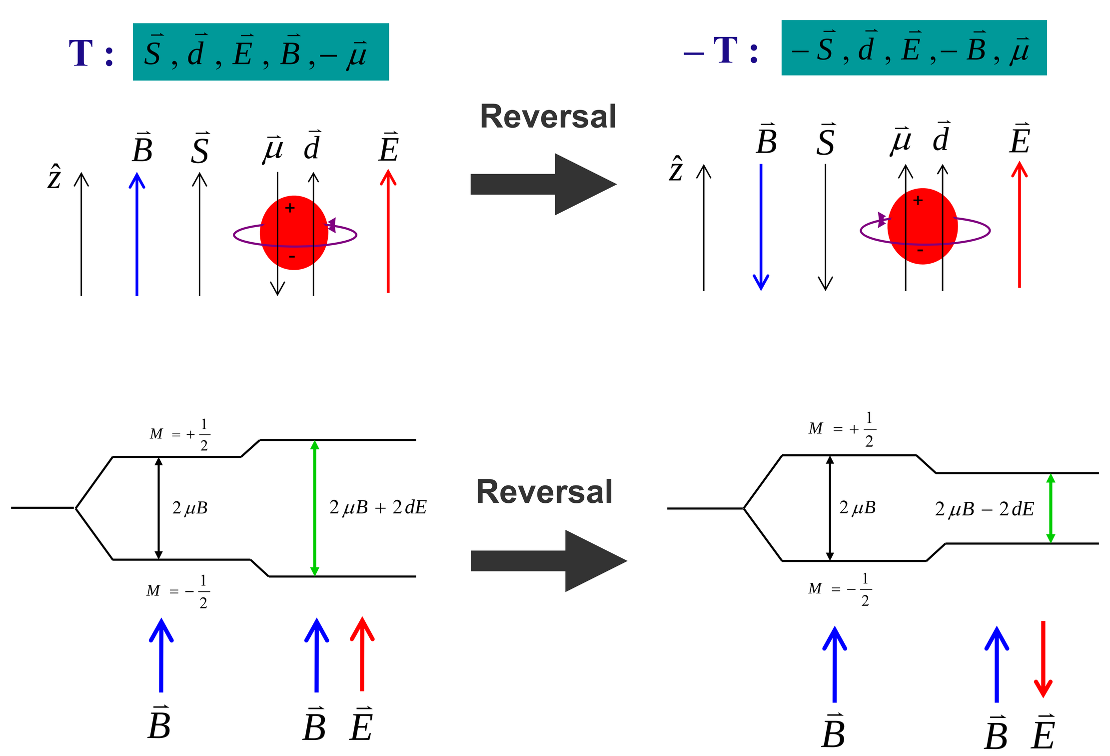
A non-zero edm would provide the evidence for new particle interaction that are not included in the SM.

If we do not detect an edm, we strongly constrain new models of physics.

→ simple spin-1/2 particle in electric and magnetic fields:

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -(\mu\vec{B} + d\vec{E})\cdot\frac{\vec{S}}{|S|}$$

$$\vec{\mu} = \mu\frac{\vec{S}}{S} \qquad \vec{d} = d\frac{\vec{S}}{S}$$

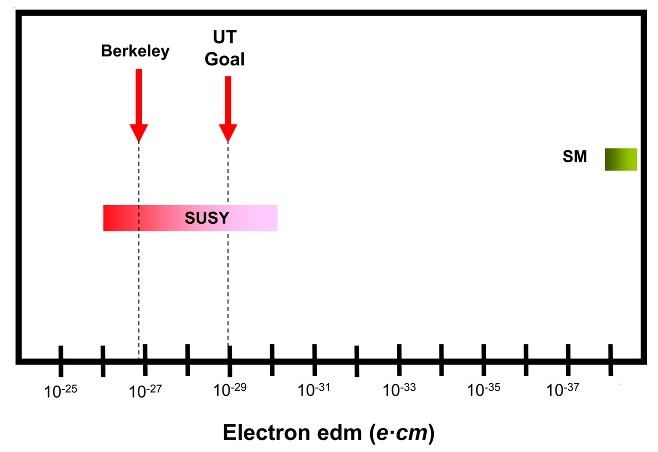


A linear energy splitting between the upper and lower states due to the interaction between **E** and d is the signature of a permanent EDM.

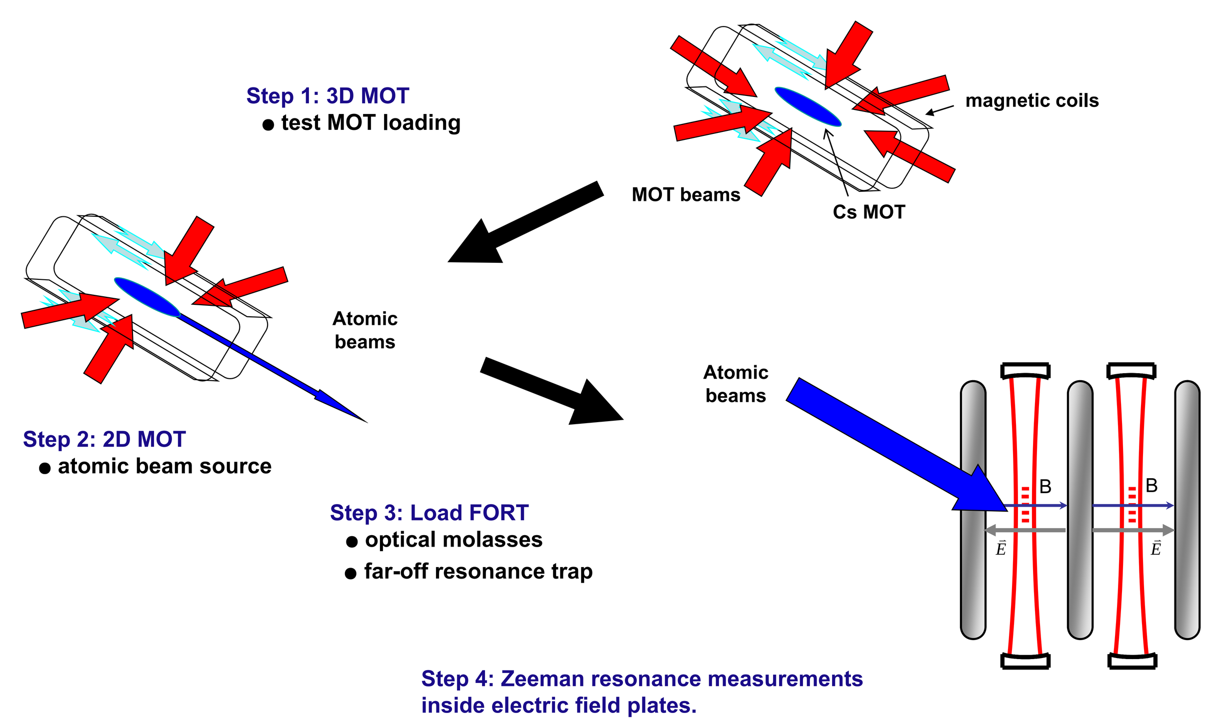
- No edm of any particle has been discovered yet.
- SM leads to an electron edm d_e of the order of 10^{-38} e ·cm.
- Extensions of the SM such as supersymmetric theories do allow that d_e could be as large as the current bound.

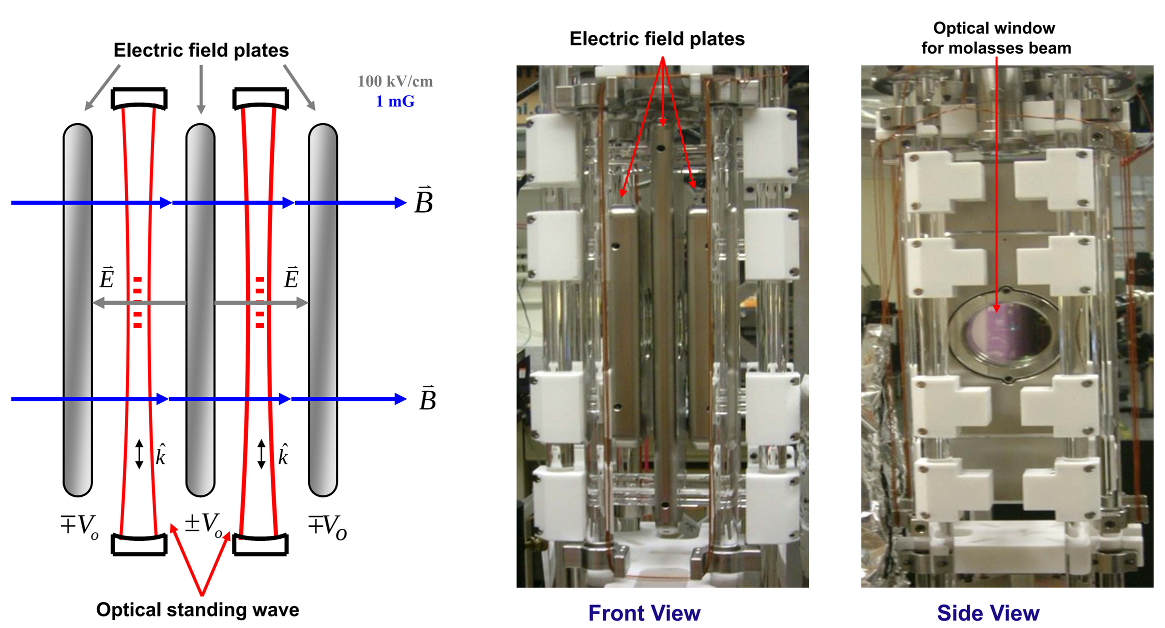
- Current experimental bound obtained by Commins' group at UC-Berkeley.

→ $\boxed{|d_e| < 1.6\times10^{-27} e\cdot cm}$



The Experiment process





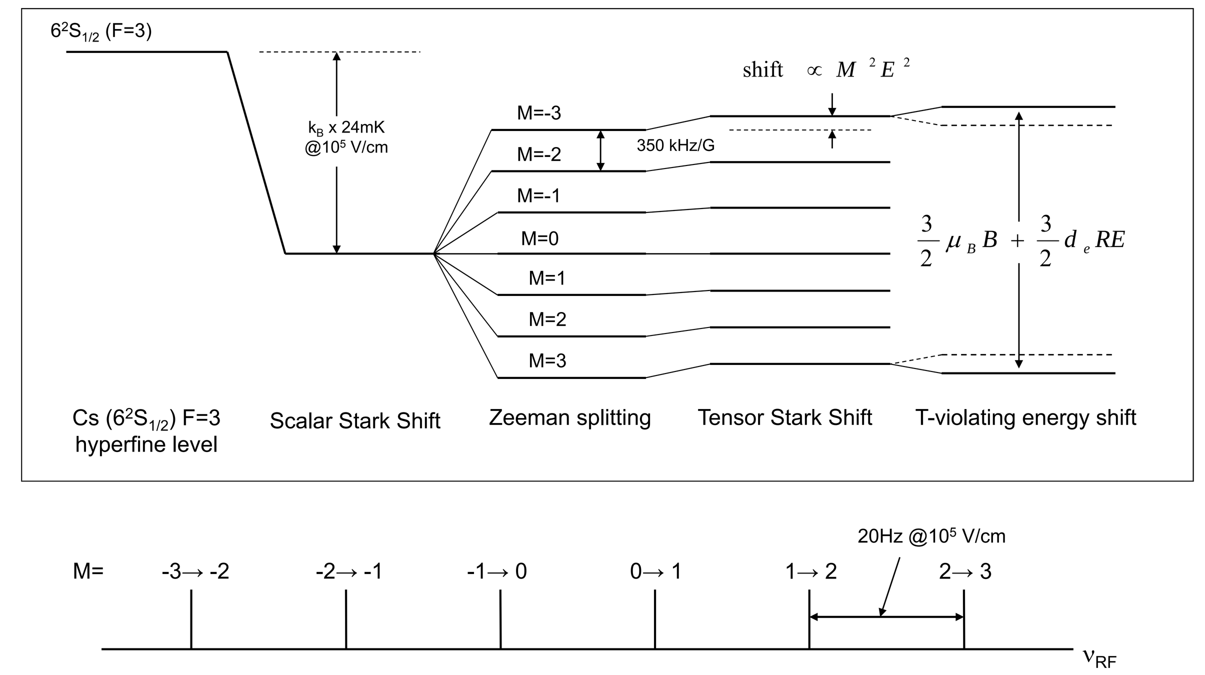
- Collect Cs atoms in regions between electric field plates with optical molasses
- Hold atoms in a far off resonance optical trap
- Apply parallel electric and magnetic fields
- Reverse electric field and measure change in energy splitting due to atomic edm, d_{Cs}

$$\boxed{d_a = R d_e}\ \text{, where } R \propto Z^3\alpha^2$$

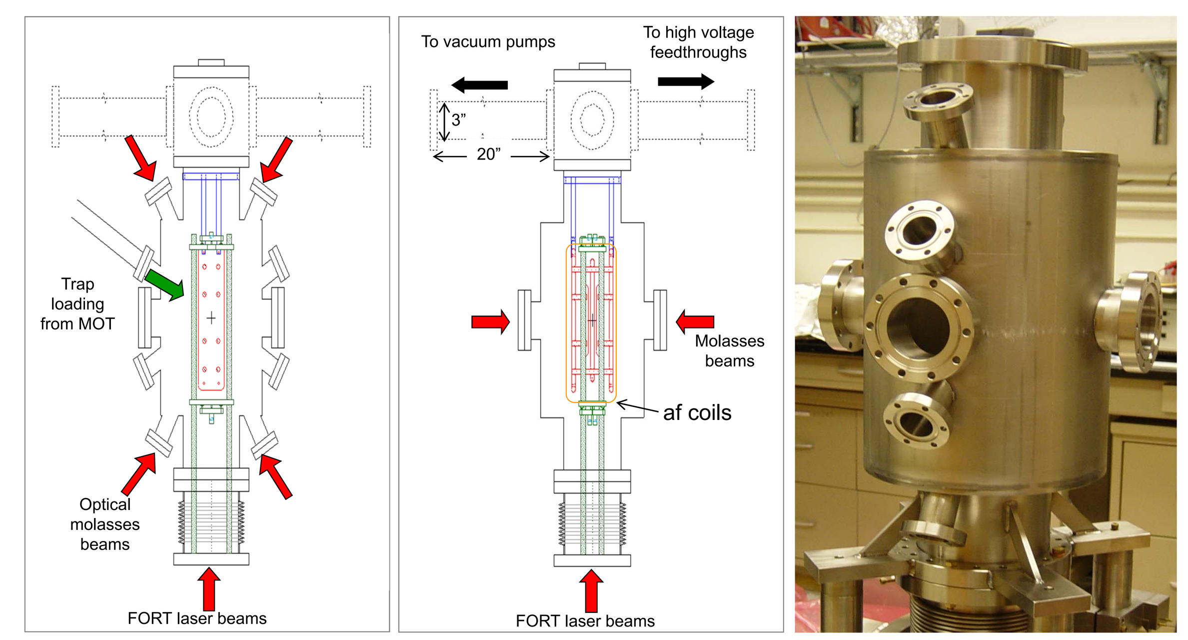
atomic edm　　electron edm

R is the "enhancement factor" , where $R_{Cs} \propto 120$

- Energy level shifts of F=3 ground state Cs in external fields



The Apparatus



The Advantages of our method

- Coherent interaction time, τ, can be > 1 sec allowing for much narrower Zeeman resonance linewidths
  - e.g. $\tau = 10$s → linewidth $= \frac{1}{2\tau} = 0.05Hz$
- No $\vec{v}\times\vec{E}$ effect
  - $\langle\vec{v}\rangle = 0$ in a trap ⟶ $\langle\vec{v}\times\vec{E}\rangle = 0$
- Large electric field, ~100kV/cm
- Strong localization of atoms minimizes problems with uncontrolled field inhomogeneity

The sensitivity limits

- Statistical uncertainty
  - Probe atoms with Ramsey Method
  - Statistical error, $\delta\upsilon_s$, is due to shot noise in number of atoms making spin transition

$$\delta d_e = \frac{2h\delta\upsilon}{3RE} \qquad \delta\upsilon = \frac{1}{2\pi\sqrt{TN\tau}}$$

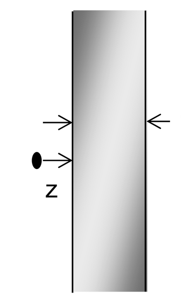
  - Two experimental regions doubles the number of atoms, reduces error by factor $\sqrt{2}$

Sample numbers

	δd_e	$\delta\nu$	T	τ	N (per side)
current bound →	10^{-27}e·cm	6.25×10^{-6} Hz	10^5 s	10 s	670
	10^{-28}e·cm	6.25×10^{-7} Hz	10^5 s	10 s	6.7×10^4
	10^{-29}e·cm	6.25×10^{-8} Hz	10^5 s	10 s	6.7×10^6

- Magnetic field noise
  - Johnson noise current-induced magnetic noise

: Use glass plates with conductive coating



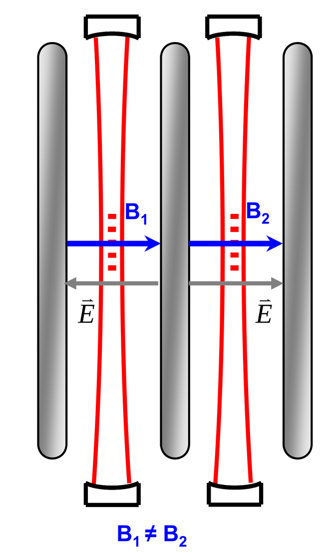
$$B_{noise} = \mu_o\sqrt{\frac{k_B T\sigma}{8\pi}\frac{W}{z(z+W)}}$$

$W = 1\,\mu m$
$z = 2.5\,mm$
$\sigma_{ITO} = 1\times10^4(\Omega\cdot m)^{-1}$

$$B_{noise} = 6.0\times10^{-16}\frac{T}{\sqrt{Hz}}$$

$$B'_{noise} \sim \frac{B_{noise}}{z} = 2.4\times10^{-15}\frac{T}{cm\sqrt{Hz}}$$

- the noise in $\Delta B = (B_1 - B_2)$ from the field gradient between two plates region



· The frequency difference between two region:

$$h\delta(\Delta\nu) = \frac{3}{2}\mu_B\delta(\Delta B) + 2\left(\frac{3}{2}RE\right)\delta d_e$$

· $\Delta B = B'D$**, where** $B' = \frac{\partial B}{\partial z}$ **and** D **=Separation between two regions**

· The noise in ΔB ~ less than the statistical noise in Δ ν

$$\frac{3}{2}\mu_B\delta(\Delta B) \le h\delta(\Delta\nu)$$

$$B'_{noise} = \frac{RE\delta d_e}{\mu_B D}$$

for D=1.5cm

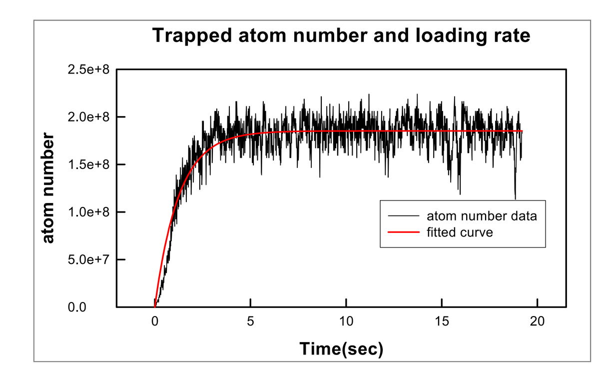
$B'_{noise} = 8.7\times10^{-14}\frac{T}{cm\cdot\sqrt{Hz}}$ for $\delta d_e = 10^{-27}e\cdot cm$

$B'_{noise} = 8.7\times10^{-15}\frac{T}{cm\cdot\sqrt{Hz}}$ for $\delta d_e = 10^{-28}e\cdot cm$

$B'_{noise} = 8.7\times10^{-16}\frac{T}{cm\cdot\sqrt{Hz}}$ for $\delta d_e = 10^{-29}e\cdot cm$

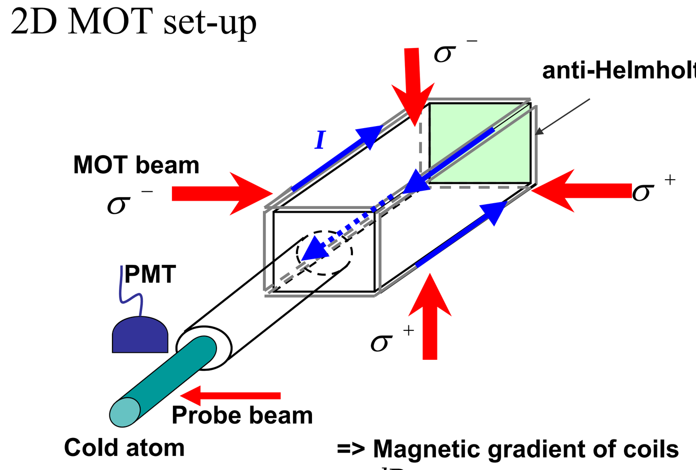
Experimental progress

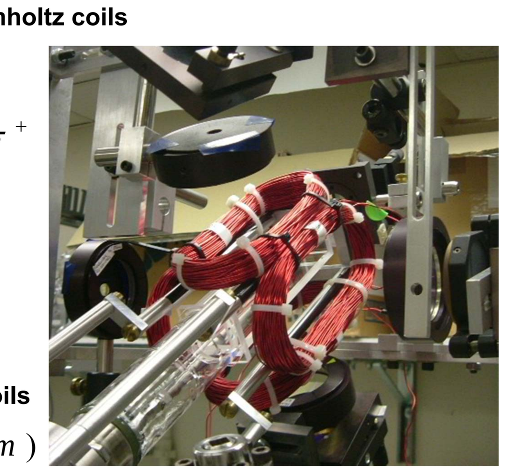
- 3D MOT test



- Total number of the steady MOT
  $N = 1.85\times10^8$
- The loading rate and time
  $\Lambda = 1.47\times10^8\,atoms/s$
  $\tau = 1.26s$

- 2D MOT set-up





=> Magnetic gradient of coils

$$\frac{dB}{dz} = 5.1\times I\,(G/cm)$$

Conclusions

- We plan to achieve a measurement sensitivity for the electron edm of $\delta d_e \le 10^{-29}$ e·cm
- Our method eliminates the most important systematic errors, proportional to atomic velocity, which have limited previous experiments
- Preliminary issues **:** Optical molasses, FORT, the spin precision frequency measurement