Laser-trapped Ra-225 for an electric dipole moment search


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Department of Energy, Office of Science, Nuclear physics
Laser-trapped Ra-225 for an electric dipole moment search

Outline

• Hg-199
• Enhancement due to octupole deformation
• Ra-225 and our scheme
• Radium atomic structure
• Laser-trapped radium!
• Blackbody-assisted repumping?
• Expected systematics and noise
• Plans
**EDM Measurement**

\[ H = -(\mu B + dE) \cdot I/I \]

\[ \nu_1 = \frac{2\mu B + 2dE}{h} \]

\[ \nu_2 = \frac{2\mu B - 2dE}{h} \]

\[ d \approx \frac{h(\nu_1 - \nu_2)}{4E} = \frac{h \Delta \nu}{4E} \]

Single atom measured over single coherence time \( \tau \):

\[ \delta d \approx \frac{\sqrt{2h}}{8\pi E\tau} \]

\( N \) atoms measured over time \( T \) with efficiency \( \varepsilon \):

\[ \delta d \approx \frac{h}{4\pi E\sqrt{\tau NT \varepsilon}} \]
The Seattle $^{199}$Hg EDM Experiment

M. V. Romalis, W. C. Griffith, J. P. Jacobs and E. N. Fortson

d($^{199}$Hg) = - (1.06 ± 0.49 ± 0.40) $10^{-28}$ e cm

- E = 10 kV/cm
- B = 15 mG
- dB<25 ppb (100s)
- dν = 0.4 nHz
- Double cell
T-violating interaction -> atomic EDM

Nuclear charge is screened from applied electric fields by electrons.

But, if dipole moment distribution is different than charge distribution, and there is a gradient in the electronic wavefunction, then the atomic EDM is proportional to the nuclear Schiff moment:

\[
d_z(V_{PT}) = k S_z(V_{PT})
\]

\[
\langle \vec{S} \rangle = \left\langle \frac{e}{10} \sum_p \left( r_p^2 - \frac{5}{3} r_{ch}^2 \right) \vec{r}_p \right\rangle
\]

V.A. Dzuba et al., PRA 66, 012111 (2002)
Density distributions of the radium isotopes

Contours of constant density for series of even-N radium (Z-88) isotopes

J. Engel et al., PRC 68, 025501 (2003)
T-violating interaction -> atomic EDM

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But, if dipole moment distribution is different than charge distribution, and there is a gradient in the electronic wavefunction, then the atomic EDM is proportional to the nuclear Schiff moment:

\[
d_z (V_{PT}) = k \ S_z (V_{PT})
\]

\[k\]

Atomic

Nuclear

<table>
<thead>
<tr>
<th>Element</th>
<th>Schiff Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-129</td>
<td>0.38</td>
</tr>
<tr>
<td>Hg-199</td>
<td>-2.8</td>
</tr>
<tr>
<td>Rn-223</td>
<td>2.0</td>
</tr>
<tr>
<td>Ra-225</td>
<td>-8.5</td>
</tr>
</tbody>
</table>

V.A. Dzuba et al., PRA 66, 012111 (2002)
Enhancement due to octupole deformation

With no correlation between spin and intrinsic deformation:

\[
\langle \Psi^+ | S_{\text{int}} | \Psi^+ \rangle = 0
\]

But, with a T-, P-odd interaction \(V_{PT}\):

\[
\Psi = \Psi^+ + \alpha \Psi^-
\]

\[
\alpha = \frac{\langle \Psi^+ | V_{PT} | \Psi^- \rangle}{\Delta E}
\]

So, in the lab frame we see:

\[
\langle S_z \rangle = 2\alpha S_{\text{int}} \frac{I}{I + 1}
\]

Enhancement: \(\text{EDM(225Ra) / EDM(199Hg)}\)

<table>
<thead>
<tr>
<th>Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
<th>Isotensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SkM*</td>
<td>1500</td>
<td>900</td>
<td>1500</td>
</tr>
<tr>
<td>SkO'</td>
<td>450</td>
<td>240</td>
<td>600</td>
</tr>
</tbody>
</table>

*PRL 94 232502 (2005), PRC 72 045503 (2005)*

Ra-225:
Spin \(I = 1/2\) (like Hg-199)
\(t_{1/2} = 15\) days

Haxton and Henley; Auerbach, Flambaum & Spevak; Dobaczewski, de Jesus & Engel
Advantages:

• ‘Efficient’ use of the rare and radioactive $^{225}\text{Ra}$ atoms
• Small sample in an UHV allows a high electric field (> 100 kV/cm)
• Long coherence times (~ 300 s)
• Cold atoms: negligible “$v \times E$” systematic effect

How do we do this measurement on rare and radioactive alkaline earth atoms?

• atomic beam is too inefficient
• no Ra vapor at reasonable temp

--> Laser-cooling and trapping
How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

\[ \delta d = 10^{-28} \text{ e cm} \]

**Statistical uncertainty:**

\[ \delta d = \frac{\hbar}{2E\sqrt{\tau}N\varepsilon T} \]

- Oven: $^{225}\text{Ra}$
- Transverse cooling
- Zeeman Slower
- Laser-cooling and trapping
- Magneto-optical trap
- Optical dipole trap
- EDM measurement

- 20 days
- 100 kV/cm
- 300 s
- $10^7$
- 0.25
How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping

**Statistical uncertainty:**

\[ \delta d = \frac{\hbar}{2E\sqrt{\tau N\varepsilon T}} \]

- $100 \text{ kV/cm}$
- $300 \text{ s}$
- $10^4$
- $0.25$
- $2 \text{ days}$

\[ \delta d = 10^{-26} \text{ e cm} \]

*With enhancement competitive with Hg-199*
Radium Atom

Experimental work:
Rasmussen (1934)

\[ \begin{align*}
\text{Energy (cm}^{-1}\text{)} & : 15000, 10000, 0 \\
\text{Levels} & : 1^1\!S_0, 3^3\!P_0, 3^3\!P_1, 3^3\!P_2, 1^1\!D_2, 3^3\!D_1, 3^3\!D_2, 3^3\!D_3 \\
\text{Isotopes} & : \\
\text{Mg} & : 12, 24.31 \\
\text{Ca} & : 20, 40.08 \\
\text{Sr} & : 38, 87.62 \\
\text{Ba} & : 56, 137.33 \\
\text{Ra} & : 88, 226
\end{align*} \]
Radium Atom

Experimental work:
Rasmussen (1934)
Russell adjustment (1934)

Energy (cm⁻¹)

1S₀

1P₁

3P₂

3P₁

3P₀

1D₂

3D₃

3D₂

3D₁

12 Mg
24.31

20 Ca
40.08

38 Sr
87.62

56 Ba
137.33

88 Ra
(226)
Radium Atom

Experimental work:
Rasmussen, Russell (1934)
Armstrong (1979)
ISOLDE (1983-1988)

Energy (cm⁻¹)

1P₁

20000

3P₂

15000

3P₁

10000

3P₀

0

1S₀

1D₂

3D₃

3D₂

3D₁

12 Mg 24.31
20 Ca 40.08
38 Sr 87.62
56 Ba 137.33
88 Ra (226)
Radium Atom

Experimental work:
Rasmussen, Russell (1934)
Armstrong (1979)
ISOLDE (1983-1988)

Temperature $\sim \frac{\hbar \Gamma}{4\pi k_B} \sim 10 \, \mu K$
$v \sim 3 \, \text{cm/s}$

Dzuba et al., PRA 73, 032503 (2006)
*Scielzo et al., PRA 73, 010501(R) (2006)
Where do we get Ra-225?

\[
\begin{align*}
229\text{Th} & \xrightarrow{\alpha} 225\text{Ra} & 7300 \text{ yr} \\
225\text{Ra} & \xrightarrow{\beta} 225\text{Ac} & 15 \text{ days} \\
225\text{Ac} & \xrightarrow{\alpha} \text{Fr, At, Bi...} & \sim 4 \text{ hours} \\
\text{Fr, At, Bi...} & \xrightarrow{\alpha,\beta} 209\text{Bi} & \text{stable}
\end{align*}
\]

1 mCi \(^{225}\text{Ra}\) (20 nano-g)
+ Al foil
+ 50 mg Ba

Reduces RaO
Passivates surfaces
Optical tracer

For trap development, using
\(^{226}\text{Ra} \ (t_{1/2}=1600 \text{ yr})\)
\(~1 \mu\text{Ci} \ (\sim 1 \mu\text{g})\)
Ra-225 atomic beam

$^{1}S_0 \left| F=1/2 \right> \rightarrow \left| 3P_1 \right| F=3/2 >$

13999.269(1) cm$^{-1}$

N. D. Scielzo et al., PRA 73, 010501 (2006)

Shifts NIST AD # by 700 MHz

ALSO OBSERVED $|F=1/2> \rightarrow |F=1/2>$

Laser locking transition

Wavenumber (cm$^{-1}$)

13999.23 13999.25 13999.27
Fluorescence
Time (ns)

Predictions:
505 ns V. A. Dzuba et al., PRA 61, 062509 (2000)
362 ns V. A. Dzuba et al., PRA 73, 032503 (2006)

$$\tau = 422 \text{ ns} \pm 20 \text{ ns}$$

N. D. Scielzo et al., PRA 73, 010501 (2006)
Ra-226 atom trap

N = 1,000 trapped Ra-226 atoms
N = 30 trapped Ra-225 atoms
Repump worked! Russell was right.

Ra trap: Loading and Lifetime

Oven flux (Ra-226): $F \sim 2 \times 10^9$ atoms/s
Trapping efficiency: $\varepsilon \sim N/(F\tau) \sim 7 \times 10^{-7}$

Loading

Lifetime

$\tau = 1.1 \text{ s}$ (Vacuum limited)
Single radium atoms in the trap

Counts

Time (seconds)

Two atoms
One atom
No atoms
Repump spectrum

Ra-226
Ra-225 (100x)

3/2 → 3/2
3/2 → 1/2
1/2 → 3/2
1/2 → 1/2

Wavenumber (cm⁻¹)

Trapped atoms (arb. un.)
**Hyperfine constants and isotope shift on $^3D_1 - ^1P_1$**

Repump laser is heterodyned with 2nd laser locked to stabilized Fabry-Perot.

Ra-226

$^1P_1$ → $^1P_1$

$^3D_1$

$3/2$ → $3/2$

$540.2(2.0)$ MHz

$4196.0 (2.3)$ MHz

ISOLDE: 4195(4) MHz*

Ra-225

$1/2$ → $1/2$ 6999.83 cm$^{-1}$

$7031.5 (2.3)$ MHz


Repump spectrum

Ra-226

Ra-225 (100x)

\[ \begin{align*}
3/2 \rightarrow 3/2 & \quad \text{peak at 6999.8 cm}^{-1} \\
3/2 \rightarrow 1/2 & \quad \text{peak at 6999.7 cm}^{-1} \\
1/2 \rightarrow 1/2 & \quad \text{peak at 6999.6 cm}^{-1} \\
1/2 \rightarrow 3/2 & \quad \text{peak at 7000 cm}^{-1}
\end{align*} \]
Radium atom repump dynamics

1429nm Repumping to $^1P_1$

Blackbody spectrum @ 298K
$(k_B T/\hbar c) = 210 \text{cm}^{-1}$

298 K thermal transition rates

$B_{ij} \rho(v_{ij},T) = \frac{A_{ij}}{e^{E/k_B T} - 1}$, $B_{ji} = \frac{g_i}{g_j} B_{ij}$

Dzuba et al., PRA 73, 032503 (2006)
Blackbody repumping

Repump OFF

Repump ON

Laser-cooling

3P₁

3P₀

654 µs

3D₁

Repumping to ¹P₁ (482nm photon)

298 K thermal transition rates

3D₁ lifetime ≥ 510 ± 60 µs

2.8 ± 0.3 E2 s⁻¹

Where we are and where we’re going ...

We have successfully ...

- Laser-cooled and trapped Ra-225 and Ra-226
- Measured transition frequencies, lifetimes, and hyperfine splittings

Oven: Ra-225
Transverse cooling
Zeeman Slower
Magneto-optical trap
Optical dipole trap
EDM measurement

We are here!
Optical dipole trap laser

- Radium, 5 Watts, 60µm spot
- Erbium fiber laser

\[ U_{dip} \propto -\frac{1}{4} \alpha |E_D|^2 \]

\[ T_D \approx 10 \ \mu K \]
**EDM measurement**

$\nu t \approx \frac{1}{2\pi} \frac{N^+ - N^-}{N^+ + N^-} + m$

$B = 10 \text{ mG}: \nu = 10 \text{ Hz} \ldots E = 100 \text{ kV/cm}: d = 10^{-26} \text{ ecm}$?

$dv = 1 \text{ \mu Hz} = 30 \text{ \mu Hz} / (1000)^{1/2}$
Environmental magnetic fields (need < 30 nG over 300 s)

Magnetic shielding: $>10^4$ suppression
Stable current supply for applied B field
(need <3ppm over 300s)
Systematics and noise

Largest systematics arise from magnetic fields which change with direction of applied electric field

Leakage current between plates could run in loop causing a magnetic field $B_{\text{leak}}$ which changed direction with $E$

Motional magnetic field $B_{\text{mot}} = 1/c^2 v \times E$ changes direction with $E$

Electric quadrupole terms $H \sim |E|^2$ may lead to systematic with incomplete field reversal (0 for spin-1/2)

Geometric phase small due to small trap size, velocity

Collisions? Low density, Cold spin-polarized fermions
Possible dipole trap systematics and noise

Systematics:

COM Potentials? $|E_{HV}|^2 \sim 100x|E_D|^2$
Dipole + HV potential + gravity

\[ U(r) = \]
\[-\alpha/2 \left( |E_{HV}(r)|^2 + 1/2 |E_D(r)|^2 \right) + Mg x \]

Trap stability?
  - Need plates parallel to 10 mrad
Systematics? 10 \( \mu \)m shift with reversal?
  - Need < 100 nG/mm at center
Possible dipole trap systematics and noise

Systematics:

**COM Potentials?** \( |E_{HV}|^2 \sim 100x|E_D|^2 \)

E-field mixes opposite parity states, can cause magnetic dipole shifts

Noise, coherence limiting mechanisms:

Residual circular polarization of dipole laser provide a vector light shift, linear in \( m \) (no tensor shift \( I=1/2 \))

*Use trans lin pol, lattice*

M. V. Romalis and E. N. Fortson, PRA 59, 4547 (1999)

C. Chin et al., PRA 63, 033401 (2001)
We have successfully ...

- Laser-cooled and trapped Ra-225 and Ra-226
- Measured transition frequencies, lifetimes, and hyperfine splittings

We are now ...

- Preparing to load optical dipole trap
- Improving front end
- Developing EDM apparatus for $10^{-26}$ ecm measurement.
  Statistics within reach with current efficiencies and:
  
  10 mCi, $E=100$ kV/cm, $\tau=300s$
Kr, He, and Ra :) atom trappers