EDM searches on atoms with deformed nuclei: Radium-225


October 9th, 2006
Flavour in the Era of the LHC, 4th meeting
EDM and g-2 miniworkshop

Department of Energy, Office of Science, Nuclear physics
EDM searches on atoms with deformed nuclei: Radium-225

Outline

• EDMs and new physics
• Hg-199
• Enhancement due to octupole deformation
• Ra-225
• Our scheme: laser-cooling + optical dipole trap
• Progress and plans
What is an EDM?

A permanent electric dipole moment (EDM) is aligned along the spin axis and violates both time-reversal symmetry and parity.

Standard Model predicts EDMs many orders of magnitude below current levels of experimental sensitivity ... BUT

Theories beyond SM predict EDMs within range of current experiments

Where has all the antimatter gone? Need stronger CP violation
EDM Measurement

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

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

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

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

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 \( \varepsilon \):

\[ \delta d \approx \frac{h}{4\pi E \sqrt{\tau NT \varepsilon}} \]
Neutron EDM limits: the first 50+ years

Theoretical Prediction:
- Electromagnetic
- Milliweak
- Weinberg
- Multi-Higgs
- Supersymmetry
- Cosmology
- Superweak
- Standard Model
EDM Searches

Experiments

Nuclear
- Neutron
- Diamagnetic Atoms (Hg, Xe, Ra, Rn)
- Paramagnetic Atoms (Tl, Cs, Fr)
- Molecules (PbO, YbF)

Atomic
- Atomic Theory
- Nuclear Theory

Molecular
- Atomic Theory

High Energy Theory
- QCD
- Quark EDM
- Quark Chromo-EDM
- Electron EDM

Fundamental Theory - Supersymmetry, Strings

10^{-24} \text{ eV}

1 \text{ eV}

1 \text{ MeV}

1 \text{ GeV}

1 \text{ TeV}

Courtesy of M. Romalis
Limits on CP-violating SUSY phases

Norval Fortson, Lepton moments 2006

The Seattle $^{199}\text{Hg}$ EDM Experiment

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

\[ d^{(199\text{Hg})} = -(1.06 \pm 0.49 \pm 0.40) \times 10^{-28} \text{ e cm} \]

- $E = 10 \text{ kV/cm}$
- $B = 15 \text{ mG}$
- $dB < 25 \text{ ppb (100s)}$
- $\nu = 0.4 \text{ nHz}$
- Double cell
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:

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

\[ k \quad \text{Atomic} \quad \downarrow \quad \text{Nuclear} \]

<table>
<thead>
<tr>
<th>Element</th>
<th>edm [10^{-17} cm/fm^3]</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)

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

a 'radially-weighted dipole moment'
Density distributions of the radium isotopes

Contours of constant density for series of even-N radium isotopes

J. Engel et al., PRC 68, 025501 (2003)
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 \textit{Schiff moment}:

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

\( k \) is a constant in \([10^{-17} \text{ cm/fm}^3]\).

<table>
<thead>
<tr>
<th>Substance</th>
<th>EDM [10^{-17} \text{ cm/fm}^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-129</td>
<td>0.38</td>
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</table>

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

<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
# EDM Searches in heavy diamagnetic atoms

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Current Limit (e cm)</th>
<th>Institution</th>
<th>Factor of Improvement Meas d(A)</th>
<th>T-odd Sensitivity</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-129</td>
<td>(0.7 ± 3.3)E-27</td>
<td>Princeton</td>
<td>10³ – 10⁹</td>
<td>0.47</td>
<td>Liquid cell</td>
</tr>
<tr>
<td></td>
<td>Michigan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hg-199</td>
<td>-(1.1 ± 0.6)E-28</td>
<td>Washington</td>
<td>2-4</td>
<td>4</td>
<td>4 cells</td>
</tr>
<tr>
<td></td>
<td>Washington</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rn-223</td>
<td>N/A</td>
<td>Michigan &amp; TRIUMF</td>
<td>~ Hg</td>
<td>2000</td>
<td>Cell</td>
</tr>
<tr>
<td>Ra-225</td>
<td>N/A</td>
<td>Argonne, KVI</td>
<td>~ Hg</td>
<td>2500</td>
<td>Trap</td>
</tr>
</tbody>
</table>
E929: TRIUMF Radon EDM Experiment

- Measure $^{223}$Rn levels and octupole deformation (8-$\pi$ detector)
- Collect and polarize radon
- Measure $^{223}$Rn
Radon EDM Progress

Noble gas (Xe) collected and transferred to cell on-line
- High efficiency: 43% is 3/4 of $\varepsilon_{\text{max}}$ (@TRIUMF)

$^{209}\text{Rn}$ polarized once again (@ Stony Brook)
Systematic studies feasible

$^{223}\text{Rn}$ EDM projections ($t_2=100$ s)

**Gamma Anisotropy (A=0.2)**

$$N_\gamma = 2 \times 10^{12} \text{ (Tigress count rate limit - 3 months)}$$
$$\sigma_d = 2 \times 10^{-27} \text{ e-cm (10x better than } ^{199}\text{Hg)}$$

**Beta Asymmetry**

<table>
<thead>
<tr>
<th>Rate</th>
<th>$\sigma_d$ (100 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 10^7$</td>
<td>$6 \times 10^{-28}$ e-cm</td>
</tr>
<tr>
<td>$10^9$</td>
<td>$1 \times 10^{-28}$ e-cm</td>
</tr>
</tbody>
</table>

Tim Chupp
U of Michigan
Advantages:

• ‘Efficient’ use of the rare and radioactive $^{225}$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

EDM measurement on Ra-225

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

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

$\rightarrow$ 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

\[ \rightarrow \text{Laser-cooling and trapping} \]

**Statistical uncertainty:**

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

- 100 kV/cm
- 300 s
- 10^7
- 0.05

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

100 days
**Where do we get Ra-225?**

229Th → \( \alpha \) 225Ra → \( \beta \) 225Ac → \( \alpha \) Fr, At, Bi... → \( \alpha, \beta \) 209Bi

- 229Th : 7300 yr
- 225Ra : 15 days
- 225Ac : 10 days
- Fr, At, Bi... : ~ 4 hours
- 209Bi : stable

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}) \ 
\sim 1 \mu\text{Ci} \ (\sim 1 \mu\text{g})*
Gamma-ray detection of Ra-225

$^{225}$Ra can be monitored by watching for its characteristic $\gamma$-ray line.

$^{225}$Ac

$^{217}$At

$^{213}$Bi

$^{213}$Po

$t_{1/2} = 14.9$ d

30% $\beta^-$

70% $\gamma$

40 keV $\gamma$-ray

12% $\gamma$

218 keV $\gamma$-ray

26% $\gamma$

441 keV $\gamma$-ray

$^{40}$ keV $\gamma$-ray

$^{221}$Fr

$^{217}$At$^+$

$^{213}$Bi

$^{225}$Ac

$^{213}$Po

$^{225}$Ra

Ge detector

Counts (Hz)

Energy (keV)
$^{225}\text{Ra}$ atomic beam ($\sim 200 \, \mu\text{Ci}$ source)

- 200 $\mu\text{Ci} \, ^{225}\text{Ra}$ decay rate
- $^{225}\text{Ra}$ from oven (atoms/sec)
- Temperature (C)

- Ba only
- or
- Ba + Al foil
**Experimental work:**
Rasmussen, Russell (1934)
Armstrong (1979)
ISOLDE (1983-1988)

**Dzuba et al., PRA 73, 032503 (2006)**
*Scielzo et al., PRA 73, 010501(R) (2006)*
Ra-225 atomic beam

$^1S_0$ |F=1/2> $\rightarrow$ $^3P_1$ |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>
Ra $7s7p \ ^3P_1$ lifetime measurement

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

- Loading efficiency ~ 7x10^-7
- ~2,000 trapped atoms
- 1-2 s lifetime
- Repump critical
Repump spectrum

\[ {^1P_1} \rightarrow {^3D_1} \]

Ra-226

Trapped atoms (arb. un.)

Wavenumber (cm\(^{-1}\))

6999.6  6999.7  6999.8  6999.9  7000  7000.1
Repump spectrum

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

Trapped atoms (arb. un.)

Wavenumber (cm⁻¹)

Ra-226

Ra-225 (100x)
Hyperfine constants and isotope shift on $^3D_1 - ^1P_1$

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

$^1P_1$

$^3D_1$

6999.83 cm$^{-1}$

Ra-226

Ra-225

F

539(4) MHz

4196(2) MHz

ISOLDE: 4195(4) MHz*

Radium atom repump dynamics

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

\[ B_{ij} \rho(\nu_{ij}, T) = \frac{A_{ij}}{e^{E/\hbar k_B T} - 1}, \quad B_{ji} = \frac{g_i}{g_j} B_{ij} \]

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

Repump OFF

Repump ON

\( \text{3P}_1 \) (482nm photon)

Laser-cooling

\( \text{3P}_0 \)

\( \text{654 \mu s} \)

\( \text{298 K thermal transition rates} \)

\( 2.8 \pm 0.3 \times 10^2 \text{ s}^{-1} \)

\( \text{3D}_1 \) lifetime = 520 ± 60 \( \mu \text{s} \)

Preliminary!
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

We are now …
- Preparing to load optical dipole trap
- Developing EDM apparatus for \(10^{-26}\) ecm measurement.
- Statistics within reach with current efficiencies and:
  - 10 mCi, \(E=100\) kV/cm, \(\tau=300\) s
**EDM measurement**

- **B-field**
- **E-field**

\[
\nu t \approx \frac{N^+ - N^-}{N^+ + N^-} + 2\pi m
\]

- \( B = 10 \text{ mG} \): \( \nu = 10 \text{ Hz} \)
- \( E = 100 \text{ kV/cm} \): \( d = 10^{-26} \text{ ecm?} \) \( d\nu = 1 \mu\text{Hz} \)

\( ^3P_1 \, F=1/2 \)

\( m_F = -1/2 \quad +1/2 \)

\( ^1S_0 \, F=1/2 \)

Optical pumping
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** $B_{\text{mot}} = 1/c^2 \mathbf{v} \times \mathbf{E}$ changes direction with $E$

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

Collisions? Cold spin-polarized fermions

Magnetic field noise? Homogeneity?

Stable current supply $\rightarrow$ 40 ppb over 40 s
Magnetic shielding (We have trap fields!)
Possible dipole trap systematics and noise

Systematics:

COM Potentials? $|E_{\text{plat}}|^2 \sim 100 \times |E_{\text{dip}}|^2$

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)
Kr, He, and Ra :) atom trappers
**Optical dipole trap**

With conservative potential due to AC Stark shift and scalar polarizability, we can trap atoms in the focus of a red-detuned laser:

\[
U_{\text{dip}}(r) \propto -I(r) \sum_i \frac{\Gamma_i}{\omega_i^2 \left( \omega_i^2 - \Omega^2 \right)}
\]

**Sum over atomic transitions**

**Scattering rate:**

\[
\Gamma_{\text{dip}}(r) \propto I(r) \Omega^3 \sum_i \left( \frac{\Gamma_i}{\omega_i^2 \left( \omega_i^2 - \Omega^2 \right)} \right)^2
\]