Status of the Search for an EDM of $^{225}$Ra

Outline

- Why is an EDM interesting?
- Why use radium?
- How to detect an EDM
- Our plan: Source, MOT, FORT, EDM
- Status and Schedule
EDM Violates Both P and T

A permanent EDM violates both time-reversal symmetry and parity

- Neutron, Deuteron
- Diamagnetic Atoms ($^{199}\text{Hg}$, $^{225}\text{Ra}$, $^{223}\text{Rn}$)
- Paramagnetic Atoms (TI)
- Molecules (PbO)

Quark EDM
Quark Chromo-EDM
Electron EDM

Physics beyond the Standard Model: SUSY
Origin of EDM’s

- Standard Model EDM’s are due to CP violation in CKM matrix ($K^0$-system) but…
  - $e^-$ and quark EDM’s are zero at Tree Level.
  - Need at least third order to get EDM’s.
  
  • *Thus EDM’s are VERY small in the Standard Model.*

![Diagram showing the origin of EDM's with Standard Model at $10^{-31}$, New Physics encompassing SUSY, mSUGRA, multi-Higgs, L-R symmetry at $10^{-29}$ to $10^{-27}$, and Neutron at $10^{-25}$.]
The LHC is on the way.

Two Possibilities:

• The LHC doesn’t see evidence for new physics.

Window of opportunity for low energy tests to make discovery before ILC.

• The LHC observes new physics, say, SUSY.

SM has many new parameters. Low energy experiments will be necessary to pin down new parameters.
## Current Experiments in Nuclei

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Current Limit (e cm)</th>
<th>Institution</th>
<th>Nuclear Spin</th>
<th>Factor of Improvement</th>
<th>T-odd Sensitivity</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>199Hg</td>
<td>-(1.1 ± 0.6)E-28</td>
<td>Washington</td>
<td>1/2</td>
<td>2-4</td>
<td>5.6</td>
<td>4 cells</td>
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<tr>
<td>129Xe</td>
<td>(0.7 ± 3.3)E-27</td>
<td>Princeton</td>
<td>1/2</td>
<td>10^2 – 10^5</td>
<td>0.47</td>
<td>Liquid cell</td>
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<tr>
<td>225Ra</td>
<td>N/A</td>
<td>Argonne KVI</td>
<td>1/2</td>
<td>~ Hg</td>
<td>2100</td>
<td>Trap</td>
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<tr>
<td>223Rn</td>
<td>N/A</td>
<td>Michigan &amp;</td>
<td>7/2</td>
<td>~ Hg</td>
<td>2000</td>
<td>Cell</td>
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<td>TRIUMF</td>
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</tr>
<tr>
<td>D</td>
<td>N/A</td>
<td>BNL, IUCF, KVI</td>
<td>1</td>
<td>~Hg</td>
<td>10-10^3</td>
<td>Storage ring</td>
</tr>
</tbody>
</table>
EDM of $^{225}$Ra enhanced

**EDM of $^{225}$Ra enhanced:**
- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

\[ \Psi^- = (|+\rangle - |\rangle)/\sqrt{2} \]
\[ \Psi^+ = (|+\rangle + |\rangle)/\sqrt{2} \]

55 keV

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
<th>Isotensor</th>
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<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>

*Enhancement Factor: EDM ($^{225}$Ra) / EDM ($^{199}$Hg)*

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)

NB: Must include quadrupole term in Schiff operator: See C.-P. Liu et al, nucl-th/0601025

Schiff moment of $^{199}$Hg, de Jesus & Engel, PRC72 (2005)
Schiff moment of $^{225}$Ra, Dobaczewski & Engel, PRL94 (2005)
EDM Measurement

Parameters

\[ B = 10 \text{ mGauss} \]
\[ f = 11 \text{ Hz} \]
\[ E = 100 \text{ kV/cm} \]
\[ f_+ - f_- = 10 \text{ nHz} \]
\[ d = 1 \times 10^{-28} \text{ e cm} \]

\[ \hbar f_+ = 2\mu B + 2dE \]
\[ \hbar f_- = 2\mu B - 2dE \]
**Expected Statistical Accuracy**

No. of Ra atoms:
10 mCi source = 3.6 x 10^8 Ra/s
N = 1 x 10^7 atoms
Trap storage time = 300 s
E = 100 kV/cm
T = 100 days
Detection efficiency = 0.05

\[
\delta d = 1 \times 10^{-28} e - cm
\]

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

M. C. Romalis *et al*, PRL 86 (2001) 2505

Enhancement factor: Ra/Hg = 375
Search for EDM of $^{225}\text{Ra}$

Advantages of an EDM measurement on $^{225}\text{Ra}$ atoms in a trap:

- Trap allows a long coherence time (~ 300 s).
- Cold atoms result in a negligible “$v \times E$” systematic effect.
- Trap allows the efficient use of the rare and radioactive $^{225}\text{Ra}$ atoms.
- Small sample in an XHV allows a high electric field (> 100 kV/cm).

$^{225}\text{Ra}$

Nuclear Spin = $\frac{1}{2}$

Electronic Spin = 0

$t_{1/2} = 15$ days
Radium Atom Energy Level Diagram

Dzuba et al., PRA 61, 062509 (2000)

Laser-cooling on $^1S_0-^3P_1$:
- ~$2 \times 10^4$ cycling transitions
- 422 ns lifetime*
- Accel ~ 3000 m/s$^2$
- 1 G/cm MOT gradient
- $k_B T = \hbar/(2\tau) \sim 10 \mu K$
- 7 ms cooling w/o repump

Repump on $^3D_1-^1P_1$:
- 8 s cooling w/ repump
- Transition frequency?
- Isotope shift?
- Hyperfine splitting?

* N. D. Scielzo et al., PRA 73, 010501 (2006)
Argonne National Laboratory

Radium EDM Experiment
225Ra Source

229Th [→] 225Ra [→] 225Ac [→] Fr, At, Rn… [→] 209Bi

7300 yr [→] 15 days [→] 10 days [→] stable

- 10 mCi 229Th source produces 4 × 10^8 s^-1 225Ra
- Test source: 0.5 mCi 229Th
- Chemical extraction of Ra from Th
- Reduction of Ra(NO₃)₂ with Ba, Al, Ti…

Expected yield for 225Ra: 3 × 10^{10} s^-1
**225Ra from the Oven**

13 October 03 experiment

- **225Ra**
  - $t_{1/2}=14.9$ d
  - 30% $\beta^-$
  - 40 keV $\gamma$-ray

- **225Ac**
  - 70% $\alpha$

- **221Fr**
  - 12% $\alpha$
  - 218 keV $\gamma$-ray

- **217At**
  - $\alpha$

- **213Bi**
  - 26% $\alpha$
  - 441 keV $\gamma$-ray

- **137Cs**
  - $\gamma$

- **213Po**
  - $\alpha$

Graphs showing energy spectra and counts for different elements.
Spectroscopy and lifetime measurement

Radium

741.3 nm
7p $^3P_1$

$^1S_0$

7s$^2$$^1S_0$

6d $^3D_1$

~250-500 ns

250 µCi ~ 5 nano-g $^{225}$Ra
+ 100 mg Ba

Barium

791.1 nm
6p $^3P_1$

$^1S_0$

6s$^2$$^1S_0$

5d $^3D_1$

~1200±100 ns *

~250-500 ns


Notch filter

Transverse laser beam

Oven @ 700 C

Ba and Ra atomic beam

PMT
Fluorescence

$^1S_0 \ |F=1/2\rangle \rightarrow ^3P_1 \ |F=3/2\rangle$

13999.267(1) cm$^{-1}$
**Ra 7s7p ^3P_1 lifetime measurement**

Lifetime measurement cycle:

- Fluorescence
- Excitation laser

Fluorescence decay plot with a best fit line showing a lifetime of $\tau = 422 \text{ ns} \pm 20 \text{ ns}$.

N. D. Scielzo et al., *PRA* (2006)
Repump transition in $^{226}$Ra beam

$^{3}\text{D}_1 \rightarrow ^1\text{P}_1$

6999.83(1) cm$^{-1}$
(1428.606 nm)
Radium slower and trap

750 nCi $^{226}$Ra (600 nano-g)
1 mCi $^{225}$Ra (20 nano-g)

Transverse cooling

Zeeman slower

1 $\mu$s

Probe phase

~400 ms

~50 ms

Slower, Trans cooling, MOT phase

MOT

Repump

Slower

PMT
Laser-Trapping of Radium Atoms

- World's first laser trap of radium atoms: both $^{225}\text{Ra}$ and $^{226}\text{Ra}$ atoms are cooled and trapped!

- Key $^{225}\text{Ra}$ frequencies, lifetimes measured.

![Graph showing fluorescence signal versus probe frequency shift (MHz)]
Laser-Trapping of Radium Atoms

- World’s first laser trap of radium atoms: both $^{225}\text{Ra}$ and $^{226}\text{Ra}$ atoms are cooled and trapped!

- Key $^{225}\text{Ra}$ frequencies, lifetimes measured.

“So it’s a first. Everything we do is a first!”
Overall Trap Efficiency

- Monte Carlo estimate: $3 \times 10^{-6}$
- Observation: $7 \times 10^{-7}$
- Original proposal: $1 \times 10^{-4}$

Future Improvements:
- Improved transverse cooling: x 2-10
- Longer slower: x 2
- Re-pump along slower: x 3
**Optical Dipole Trap**

\[
H = -\tilde{d}E = -\frac{1}{4} \alpha E_0^2
\]

Excitation rate \( \sim \frac{\text{Intensity}}{(f_{\text{laser}} - f_{\text{atom}})^2} \)  

Trap potential \( \sim \frac{\text{Intensity}}{(f_{\text{laser}} - f_{\text{atom}})} \)

- Erbium Fiber laser: \( \lambda = 1.5 \ \mu \text{m}, \ \text{Power} = 5 \ \text{Watts} \)
- Focused to 50 \( \mu \text{m} \) diameter \( \rightarrow \) trap depth 100 \( \mu \text{K} \)
- Excitation rate \( \sim 10^{-5} \ \text{s}^{-1} \)
- Spin relaxation rate \( \sim 10^{-20} \ \text{s}^{-1} \) negligible

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

1. Polarize
2. $\pi / 2$ pulse
3. Free precess
4. $\pi / 2$ pulse
5. Measure population

Fluorescence

- Polarize
- $\pi / 2$ pulse
- Free precess
- $\pi / 2$ pulse
- Measure population

\[
\frac{P_+ - P_-}{P_+ + P_-}
\]

\[f_{\text{drive}} - f_{\text{atom}}\]
The Science

Heavy Ion
- Begin studies of rare processes in the formation of hot, dense nuclear matter (2004)
- Determine if quark-gluon plasma, the matter of the infant universe, can be made in the laboratory using colliding beams of atomic nuclei (2007)
- Begin measurements of the behavior of high-transverse-momentum particles through hot, dense, nuclear matter that is dominated by gluons (2011)

Medium Energy
- Obtain first polarized high-energy proton-proton data studying the proton spin (2006)
- Determine the strange quark content of the proton (2008)
- Begin search for an electric dipole moment of Radium-225 (2007)
- Establish basic properties of the proton, neutron, and simple nuclei using high-intensity polarized electron beams at 6 GeV (2012)

Low Energy
- Complete measurements in new regions of nuclear structure and...
Milestones

☑ 2003 – Establish Ra lab, prepare Ra oven and beam

☑ 2004 – Stabilize laser and perform laser spectroscopy of $^{225}$Ra, improve oven

☑ 2005 – Establish MOT of Ra atoms

• 2006 – Establish optical dipole trap
• 2007 – Begin EDM experiment
• 2008 - Improve statistics and systematics
• 2009 - …
Summary

• New initiative at Argonne to search for the EDM of $^{225}\text{Ra}$

• Combined advantages of optical trapping and the use of an octupole deformed nucleus

• Ultimate goal of at least x 100 improvement in sensitivity over previous experiments

• Radium-225 atoms have been optically trapped.
“Desperate Trappers”
Argonne

http://www-mep.phy.anl.gov
The End