The Ongoing Radium EDM Experiment

Matt R. Dietrich

Physics Division
Argonne National Lab

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Electric Dipole Moments and Discrete Symmetries

Electric dipole moment (EDM):
* displacement vector from a particle’s center of mass to its center of charge.
* violates both $P$-parity (spatial inversion) and $T$-time reversal symmetries:

Assuming the combination of $C$-charge conjugation (particle $\leftrightarrow$ antiparticle), $P$, and $T$ is conserved:
* $T$-violation implies $CP$-violation
* EDMs are a very sensitive probe of $CP$-violation
## EDM Sectors

- **Quark EDMs**
  - \( \theta_{QCD} \)

- **Neutron, Proton,...**

- **Diamagnetic Atoms**
  - \( \text{Xe, } Hg, \text{ Rn, Ra,...} \)
  - Molecules (TIF,...)

- **Paramagnetic Atoms**
  - \( \text{Cs,Tl,Fr} \)
  - Molecules (YbF, PbF, WC, PbO, ThO, HfF\(^+\),...)

- **Electron EDM**

### EDM Sector Experiments

<table>
<thead>
<tr>
<th>Sector</th>
<th>Exp Limit (e-cm)</th>
<th>Location</th>
<th>Method</th>
<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>( 1 \times 10^{-27} )</td>
<td>Imperial College</td>
<td>YbF molecules in a beam</td>
<td>( 10^{-38} )</td>
</tr>
<tr>
<td>Neutron</td>
<td>( 3 \times 10^{-26} )</td>
<td>ILL</td>
<td>UCN in a bottle</td>
<td>( 10^{-31} )</td>
</tr>
<tr>
<td>Nuclear</td>
<td>( 3 \times 10^{-29} )</td>
<td>U. Washington</td>
<td>(^{199})Hg atoms in a cell</td>
<td>( 10^{-33} )</td>
</tr>
</tbody>
</table>
EDM Measurements

\[ h \nu = \frac{\mu B}{S} \]
EDM Measurements

\[ h\nu_+ = \frac{\mu B + dE}{S} \]
EDM Measurements

\[ h\nu_+ = \frac{\mu B + dE}{S} \]

\[ h\nu_- = \frac{\mu B - dE}{S} \]
EDM Measurements

\[ h\nu_+ = \frac{\mu B + dE}{S} \]
\[ h\nu_- = \frac{\mu B - dE}{S} \]
\[ \nu_+ - \nu_- = \frac{2dE}{hS} \]
Schiff Moments and EDMs

Schiff Theorem (1963):
* Any permanent dipole moment of the nucleus is perfectly shielded by its electron cloud
* True for point-like nuclei, non-relativistic electrons

However, the “Schiff moment” is not shielded by this effect
* Zero for point-like, spherical nuclei
* Arises from deformations in the nucleus or its constituent nucleons
* Very large in nuclei with both a quadrupole and octupole deformation

Look for heavy nuclei with large quadrupole and octupole deformations!
The Seattle EDM Experiment

Properties of Hg-199 and experiment

- Stable
- Spin I=½ nucleus (no quadrupole moment)
- Nuclear T2 ~ 100-200 seconds
- High Vapor Pressure, $4 \times 10^{13} \text{ cm}^{-3}$ at room temperature
- High Z=80
- Nearly spherical nucleus
- Glass cell limits E field to 10 kV/cm
- Leakage current through cell is leading systematic

EDM(Hg-199) < $3 \times 10^{-29} \text{ e cm}$

If Hg nucleus is size of earth, then this is two charges separated by 220 pm

Candidate Nuclei
Candidate Nuclei

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Element</th>
<th>Atomic Number</th>
<th>Mass Number</th>
<th>Isotope</th>
<th>Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>H</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>He</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>Al</td>
<td>13</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>83</td>
<td>Ra</td>
<td>83</td>
<td>222</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>Rn</td>
<td>85</td>
<td>222</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)
Enhanced EDM Sensitivity in Ra-225

A large quadrupole and octupole deformation results in an enhanced Schiff moment.

- Auerbach, Flambaum & Spevak (1996)

Relativistic atomic structure weakens the Schiff theorem, resulting in a strong enhancement with increasing Z.

- Dzuba, Flambaum, Ginges, Kozlov (2002)

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

A closely spaced parity doublet enhances the appearance of parity violating terms in the underlying Hamiltonian.

- Haxton & Henley (1983)

\[
S \propto \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_i - E_0} + \text{c.c.}
\]

Enhancement Factor: EDM (225Ra) / EDM (199Hg)

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
<th>Isotensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIII</td>
<td>300</td>
<td>4000</td>
<td>700</td>
</tr>
<tr>
<td>SkM*</td>
<td>300</td>
<td>2000</td>
<td>500</td>
</tr>
<tr>
<td>SLy4</td>
<td>700</td>
<td>8000</td>
<td>1000</td>
</tr>
</tbody>
</table>

Schiff moment of 225Ra, Dobaczewski, Engel (2005)
Schiff moment of 199Hg, Ban, Dobaczewski, Engel, Shukla (2010)
Radium Source

- Up to 30 mCi (750 ng, 2*10^15 atoms) $^{225}$Ra sources from: National Isotope Development Center (Oak Ridge, TN)
- Test source: 5 μCi (5 μg, 1.3*10^16 atoms) $^{226}$Ra
- Integrated Atomic Beam Flux $\sim 10^9$/s $^{226}$Ra, $10^7 – 10^8$/s $^{225}$Ra
- Special Thanks: John Greene, Angel Garcia, Dave Fieramosca
- Vapor pressure $10^{13}$ cm^{-3} ... at 450C
Basic Radium Energy Level Diagram

- Level scheme similar to Sr, Yb
- 1P1 state leaky to metastable D states
- Operate instead on intercombination line at 714 nm
- 900 mW 714 nm provided by Ti:Saph, 300 mW 1429 nm provided by pigtailed diode
- Blackbody repumping
- Tremendous DC Stark shift (10⁵ a.u)
Collect Atoms in MOT

Ra(NO$_3$)$_2$+Ba Oven

Transverse Cooling

HV Electrodes

Zeeman Slower

Magnetic Shielding & Magnet Coils

0.6 mm

226$^{\text{Ra}}$ MOT

20,000 atoms

J. R. Guest et al., PRL 98 093001 (2007)

For EDM:
Ra-225
I = 1/2, J = 0
$\tau_{1/2}$ = 15 days

For Testing:
Ra-226
I = 0, J = 0
$\tau_{1/2}$ = 1600 yrs

(Low vapor pressure)
Apparatus
Contradicting Requirements

Magnetic Shielding & Magnet Coils

B Field in a MOT

B Field in an EDM Experiment
Contradicting Requirements
Optical Dipole Traps
Optical Dipole Traps

\[ U = -\frac{1}{2} \alpha E^2 \]
Optical Dipole Traps

\[
U = -\frac{1}{2}\alpha E^2 = -\frac{1}{2}\alpha \langle E^2 \rangle
\]

\[\propto -I\]
Optical Dipole Traps

\[ U = -\frac{1}{2} \alpha E^2 \]

\[ = \frac{1}{2} \alpha \langle E^2 \rangle \]

\[ \propto -I \]

Y. Arai et al., Nature 399, 446 [1999]
Transfer Atoms from MOT to “Bus” ODT

“Bus” ODT
50 W 1550 nm

Translation Stage

Lens

0.03 mm

0.6 mm

MOT + ODT
20,000 atoms

HV Electrodes

Magnetic Shielding & Magnet Coils
“Bus” ODT Atom Transport to Science Chamber

- “Bus” ODT
- Translation Stage
- HV Electrodes
- Magnetic Shielding & Magnet Coils
- Lens

Graph:
- Survival vs. Speed (mm/s)
- X-axis: 0 to 120
- Y-axis: 0 to 1
- Survival values at different speeds

Image:
- 5 mm
- 6000 atoms
- 0.03 mm
Unsuitability of Traveling Wave ODT

5 mm

B Field inhomogeneities
Reduced Coherence

DC Stark Shift
Atom Clumping/Shifting
Unsuitability of Traveling Wave ODT

B Field inhomogeneities
Reduced Coherence

DC Stark Shift
Atom Clumping/Shifting

\[ \begin{align*}
\epsilon & \quad \text{ODT E Field Polarization} \\
\sigma & \quad \text{Atom Spin} \\
b & \quad \text{ODT B Field Polarization} \\
E & \quad \text{Static E Field} \\
\end{align*} \]

\[ \begin{align*}
(\epsilon \cdot \sigma)(E \cdot b) \\
(E \cdot \epsilon)(b \cdot \sigma)
\end{align*} \]

Stark Interference

- ODT electric field interferes with the static E field to produce an EDM like signal
- Effect is suppressed with standing wave
- M. V. Romalis and N. Fortson, PRA 59, 6 4547 (1999)
Unsuitability of Traveling Wave ODT

\[ (\epsilon \cdot \sigma)(E \cdot b) \]
\[ (E \cdot \epsilon)(b \cdot \sigma) \]

Solution: Standing Wave ODT

B Field inhomogeneities
Reduced Coherence

DC Stark Shift
Atom Clumping/Shifting

Stark Interference
- ODT electric field interferes with the static E field to produce an EDM like signal
- Effect is suppressed with standing wave
- M. V. Romalis and N. Fortson, PRA 59, 64547 (1999)
Standing and Traveling Wave

$U$

400 uK

$U$
Standing and Traveling Wave
Transfer Atoms from “Bus” to “Holding” ODT

“Bus” ODT
50 W 1550 nm

Lens

Traveling Wave
“Bus” ODT

HV Electrodes

Magnetic Shielding & Magnet Coils
Transfer Atoms from “Bus” to “Holding” ODT

“Bus” ODT
50 W 1550 nm

Standing Wave
“Holding” ODT
10 W 1550 nm

Traveling Wave
“Bus” ODT

HV Electrodes

Magnetic Shielding & Magnet Coils

Lens
Transfer Atoms from “Bus” to “Holding” ODT

- **“Bus” ODT**: 50 W 1550 nm
- **Lens**
- **Laser Cooling**: 100 μW 714 nm
- **Traveling Wave “Bus” ODT**
- **Standing Wave “Holding” ODT**: 10 W 1550 nm
- **Magnetic Shielding & Magnet Coils**
- **HV Electrodes**
- **Laser Cooling and B Field**
Transfer Atoms from “Bus” to “Holding” ODT

Detuning (MHz)

Efficiency (%)

700 atoms 1.4% abs

Absorption Imaging

Fluorescence Imaging

3000 atoms 10^{10} \text{ cm}^{-3}

1.3 mm

1.3 mm

R. H. Parker et al., PRC 86, 065503
Ra-225 Trapping and Transport

~100-200 Ra-225 Atoms in Bus ODT
Ra-225 Trapping and Transport

~100-200 Ra-225 Atoms in Bus ODT

~50-100 Ra-225 Atoms in Holding ODT
Optical Pumping
Optical Pumping
Optical Pumping

$\sigma^+$

\[ \vec{\mu} \]

\[ ^1P_1(F = 1/2) \]

$\sigma^+$

\[ ^1S_0(F = 1/2) \]

\[ ^1P_1 \rightarrow ^3P_1 \quad 5.5 \text{ ns} \]

\[ 483 \text{ nm} \]

\[ ^1S_0 \rightarrow ^3P_1 \quad 420 \text{ ns} \]

\[ 714 \text{ nm} \]
Optical Pumping

\( ^1P_1(F = 1/2) \) \( \rightarrow \) \( ^1S_0(F = 1/2) \)

\( \sigma^+ \)

\( \mu^- \)

Photon (PMT) Counts

Time (microseconds)
Optical Pumping

\[ \sigma^+ \]

\[ \vec{\mu} \]

Photon (PMT) Counts

Time (microseconds)

0

700

1 microsecond
Optical Pumping

\( \sigma^+ \)

\( \mu \)

Photon (PMT) Counts

Time (microseconds)

1 microsecond

University of Virginia Nuclear Physics Seminar
Optical Pumping and State Detection

$\sigma^+$

$\vec{p}$

$^1P_1(F = 1/2)$

$\sigma^+$

$^1S_0(F = 1/2)$
Optical Pumping and State Detection

$\sigma^+$

$\mu$

$^1P_1(F = 1/2)$

$^1S_0(F = 1/2)$

$\sigma^+$

$\mu$

$^1P_1(F = 1/2)$

$^1S_0(F = 1/2)$
Precession of Radium 225

Polarization 96(10)%
Frequency 6.30(4) kHz
Reduced Chi2 19.0/15
Precession of Radium 225

![Graph showing the precession of Radium 225 with data points and error bars. The x-axis represents time in microseconds (μs), and the y-axis represents fluorescence in arbitrary units (a.u.). The data shows a sinusoidal pattern.]
And for our final trick...

\[ h\nu_{\pm} = \frac{\mu B \pm dE}{S} \]
## Status at Time of Precession

\[ \sigma_{d}^{\text{stat}} \geq \frac{\hbar}{2E \sqrt{\varepsilon N \tau T}} \]

<table>
<thead>
<tr>
<th>parameter</th>
<th>During last Ra-225 Run</th>
<th>near term goal for Ra-225</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E), electric field (kV/cm)</td>
<td>0</td>
<td>100</td>
<td>Install Completed HV System</td>
</tr>
<tr>
<td>(\tau), storage time (s)</td>
<td>7</td>
<td>100</td>
<td>Vacuum Upgrade</td>
</tr>
<tr>
<td>(N), # of atoms</td>
<td>(10^2)</td>
<td>(10^3)</td>
<td>Vacuum upgrade, increased activity, extra repump</td>
</tr>
<tr>
<td>(\varepsilon), efficiency</td>
<td>(~0.003)</td>
<td>0.1</td>
<td>STIRAP, increased atom number</td>
</tr>
<tr>
<td>(T), integration time (days)</td>
<td>(~3)</td>
<td>10</td>
<td>Improve data collection procedures</td>
</tr>
</tbody>
</table>

Phase 1 goal of \(3 \times 10^{-26} \text{ e cm (1}\sigma\) is competitive with the best limits from Hg-199
Vacuum Upgrade

~ $5 \times 10^{-11}$ Torr

100 kV/cm

B gradient $< 10 \mu$G/cm
Present Status

\[ \sigma_{d}^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N\tau T}} \]

<table>
<thead>
<tr>
<th>parameter</th>
<th>During last Ra-225 Run</th>
<th>near term goal for Ra-225</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E ), electric field (kV/cm)</td>
<td>0 \rightarrow 100</td>
<td>100</td>
<td>Install Completed HV System</td>
</tr>
<tr>
<td>( \tau ), storage time (s)</td>
<td>7 \rightarrow &gt;50 s MOT</td>
<td>100</td>
<td>Vacuum Upgrade</td>
</tr>
<tr>
<td>( N ), # of atoms</td>
<td>( 10^2 ) \rightarrow \text{x8 gain}</td>
<td>( 10^3 )</td>
<td>Vacuum upgrade, increased activity, extra repump</td>
</tr>
<tr>
<td>( \varepsilon ), efficiency</td>
<td>( \sim 0.003 )</td>
<td>0.1</td>
<td>STIRAP, increased atom number</td>
</tr>
<tr>
<td>( T ), integration time (days)</td>
<td>( \sim 3 )</td>
<td>10</td>
<td>Improve data collection procedures</td>
</tr>
</tbody>
</table>

Phase 1 goal of \( 3\times10^{-26} \) \( e \) cm (1\( \sigma \)) is competitive with the best limits from Hg-199
Phase 0 Measurement

- Using current parameters, move ahead with a demonstration run in the next few months
- Likely to result in an EDM limit near $10^{-24}$ e cm
- Due to synergy with other experiments, even measurements in the $10^{-25}$ to $10^{-24}$ e cm range puts pressure on some regions of phase space (T. Chupp)
- After this, implement upgrades to reach Phase I goals

<table>
<thead>
<tr>
<th>Phase 0</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal (e cm)</td>
<td>$10^{-24}$ (?)</td>
<td>$3 \times 10^{-26}$</td>
</tr>
</tbody>
</table>
## Projections

<table>
<thead>
<tr>
<th>Limiting Effect</th>
<th>Phase I (e cm)</th>
<th>Phase II w/Comagnetometer (e cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>$3 \times 10^{-26}$</td>
<td>$10^{-27}$</td>
</tr>
<tr>
<td>Leakage Current (10 pA)</td>
<td>$3 \times 10^{-27}$</td>
<td>$5 \times 10^{-30}$</td>
</tr>
<tr>
<td>Stark Interference</td>
<td>$5 \times 10^{-27}$</td>
<td>$5 \times 10^{-30}$</td>
</tr>
<tr>
<td>Exv Effects</td>
<td>$&lt; 2 \times 10^{-27}$</td>
<td>$5 \times 10^{-30}$</td>
</tr>
<tr>
<td>Geometric Phase</td>
<td>$10^{-35}$</td>
<td>$10^{-35}$</td>
</tr>
</tbody>
</table>
Blue Upgrade

\[ \sigma_{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N\tau T}} \]

x30 – x100 Atom Capture Efficiency

At this point, you'll need to fill in the gaps with the rest of the content from the image. The diagram shows energy levels and transitions, including:

- 483 nm PUMP
- 1428 nm and 1487 nm REPUMP
- 714 nm LASER-COOLING
- 2752 nm

The figure includes a graph with atom velocity on the x-axis and number density on the y-axis, showing a peak at 310 m/s and another at 60 m/s.
Project X

I.C. Gomes, J. Nolen et al.
Project X workshop, July 2012

Protons on thorium target: 1 mA x 1000 MeV = 1 MW

Predicted yields of some important isotopes:

Radon: \( ^{211}\text{Rn} > 10^{13} \) \( ^{223}\text{Rn} \sim 10^{11} /s \)

Francium: \( ^{213}\text{Fr} > 10^{13} \) \( ^{221}\text{Fr} > 10^{14} \) \( ^{223}\text{Fr} > 10^{12} /s \)

Radium: \( ^{223}\text{Ra} > 10^{13} \) \( ^{225}\text{Ra} > 10^{13} /s \)

Actinium: \( ^{225-229}\text{Ac} > 10^{14} /s \)

Compare \( 10^8 /s \) Today
Atoms Trappers @ Argonne
For an EDM measurement, the free precession time is 100 seconds, and so the data cycle is very long. Thus our statistics need to be dramatically improved.

Electron shelving technique allows us to increase number of photons from 3 to 1000 per atom, thereby overcoming this limitation.
For an EDM measurement, the free precession time is 100 seconds, and so the data cycle is very long. Thus our statistics need to be dramatically improved.

Electron shelving technique allows us to increase number of photons from 3 to 1000 per atom, thereby overcoming this limitation.
Our ODT lifetime now seems to be limited by laser noise, rather than vacuum.

May need to stabilize ODT power to achieve design lifetimes.

\[ \dot{Q}/U_0 = 0.0151 \pm 0.0007 \text{ 1/s} \]

\[ \tau_{\text{vac}} > 100 \text{ s} \]

Gehm et al., PRA 58, 3914 (1998)
Fluorescence Collection System for Precession Measurement

- 60 mm focal length, 2” diameter singlet
- Solid Angle 4%
- Total Efficiency: $1 \times 10^{-3}$ (later $3 \times 10^{-4}$)
Shadow Imaging

\[
\text{SNR} \approx N^{1/2} \left( \frac{\sigma}{A} \right)^{1/2} \frac{n}{\sqrt{s + 1}}
\]

- Achieve shot noise limit by careful background subtraction, not careful stabilization
- Effective collection efficiency at 1000 atoms: 1%
Yields of Enhancer Isotopes: Ra, Rn, Fr

Presently available
- Decay daughters of $^{229}$Th, National Isotope Development Center, ORNL
  - $^{225}$Ra: $10^8$ /s

Projected rates at FRIB (B. Sherrill, MSU)
- Beam dump recovery with a $^{238}$U beam
  - Parasitic operation, available ~ 150 days per year
  - $^{225}$Ra: $6 \times 10^9$ /s; $^{223}$Rn: $8 \times 10^7$ /s; $^{208-220}$Fr: $10^9 - 10^{10}$ /s.

- Dedicated running with a $^{232}$Th beam
  - $^{225}$Ra: $5 \times 10^{10}$ /s; $^{223}$Rn: $1 \times 10^9$ /s; $^{208-220}$Fr: $10^{10}$ /s;

FRIB will produce isotopes with enhanced sensitivity to fundamental symmetries, and provide opportunities for discovering physics beyond the Standard Model.
Zerodur Cavity Block

- Expected 1 MHz/K temperature drift
- Lock up to 6 lasers
- Suspended in standard 5 way cross with dowel pins
Rapid Interrogation Scheme

- Each detection pulse is also a state preparation pulse
- Therefore, a rapid sequence of pulses can be used to collect many data points from a single batch of atoms
- Requires a high magnetic field, set precession frequency to $\sim 6$ kHz
- Increase data collection rate by x40
Basic Radium Energy Level Diagram

- $^1P_1$ to $^1D_2$: 5.5 ns
- $^3P_2$ to $^3D_3$: 420 ns
- $^3P_1$ to $^3D_2$: 714 nm
- $^3P_0$ to $^3D_1$: 1550 nm ODT
- 483 nm PUMP
- 1429 nm REPUMP
- 714 nm LASER-COOLING