Towards a measurement of the mercury EDM using ultracold atoms

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Mechanisms to generate EDMs

fundamental CP-odd phases

$\theta, d_q, \tilde{d}_q, w$

neutron EDM

$C_{qe}, C_{qq}$

$\theta, d_q, \tilde{d}_q, w$

$\mathcal{G}_{\pi NN}$

$C_S, C_P, C_T$

Schiff moment $S$

EDM of paramagnetic atoms & molecules (Cs-133, Fr-210, TI-205, YbF, ThO, HfH$^+$)

EDM of diamagnetic atoms (Xe-129, Hg-199, Rn-221, Ra-225)

adapted from M. Pospelov & A. Ritz
Larmor frequency:
\[ \nu = \frac{2}{\mu B \pm 2dE} \]

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

T-violation is equivalent to CP-violation (because of CPT!)

General idea:

General concept:

The universal approach to measure EDMs
The universal approach to measure EDMs: *colder is better*

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

### neutron EDM
- Spallation sources: PSI, ESS Lund, ASS, various other institutes
- Reactor UCNs: ILL, FRM II, various other institutes
- Sussex/ILL, 2006: \(2.9 \times 10^{-26} \text{ e cm}\)

### electron EDM
- Atoms: Cs-133 (Penn State, Austin Texas, LBNL), Tl-205 (Berkeley, 2002), Fr-210 (CYRIC, Japan)
- Molecules: YbF (Ed Hinds, Imperial College, 2011), ThO (ACME collaboration, Harvard/Yale, 2018), HfF\(^+\) (Cornell/Ye, JILA, 2017)
- Ts-133: \(1.6 \times 10^{-27} \text{ e cm}\)
- Tl-205: \(1.0 \times 10^{-27} \text{ e cm}\)
- Fr-210: \(1.1 \times 10^{-29} \text{ e cm}\)
- YbF: \(1.3 \times 10^{-28} \text{ e cm}\)

### atomic EDM
- Thermal: Hg-199 (Fortson/Heckel, Seattle, 2016), Rn-221 (Chupp, TRIUMF)
- MOT: Ra-225 (Argonne, 2016)
- Liquid: Xe-129 (Chupp, U of Michigan, 2001)
- Hg-199: \(7.4 \times 10^{-30} \text{ e cm}\)
- Rn-221: \(1.4 \times 10^{-23} \text{ e cm}\)
- Xe-129: \(7.0 \times 10^{-28} \text{ e cm}\)

**next-generation experiments:**
- Higher neutron flux, improved cooling in He or D\(_2\), ...
- (n2EDM @ PSI, CryoEDM @ ILL, FRM II, ...)
- Laser cooling & magneto-optical trapping of molecules
- (Imperial, Yale, ACME, JILA, ...)

**ultracold atoms:**
- Radium-225 (Argonne)
Excluding beyond-SM theories (example: neutron EDM)

- SUSY $\phi \approx 1$
- SUSY $\phi \approx \alpha/\pi$
- Standard Model

- Multi-Higgs
- Left-Right

- quMercury 1st generation
- quMercury 2nd generation
- Target next-generation nEDM
- quMercury 2nd generation

Sussex/ILL 2006
Seattle 2016 (Hg-199 !)

adapted from Ed Hinds group
New Constraints on Time-Reversal Asymmetry from a Search for a Permanent Electric Dipole Moment of $^{199}$Hg

S. K. Lamoreaux, J. P. Jacobs, B. R. Heckel, F. J. Raab, and N. Fortson

Physics Department, University of Washington, Seattle, Washington 98195

(Received 17 August 1987)

A search for a permanent electric dipole moment of $^{199}$Hg atoms has yielded the null result $d(^{199}\text{Hg}) = (0.7 \pm 1.5) \times 10^{-26}$ $\text{e} \cdot \text{cm}$, which improves by an order of magnitude the limits on several possible interactions that violate time-reversal symmetry. The experiment was performed with the use of optically pumped atomic oscillators to measure any shift in the NMR frequency of $^{199}$Hg ($I = \frac{1}{2}$) produced by an external electric field.

5000-fold improvement over 30 years!
The Washington Hg-199 experiment

First Measurement of the Atomic Electric Dipole Moment of $^{225}$Ra

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R. J. Holt,$^{1}$ W. Korsch,$^{1}$ Z.-T. Lu,$^{1,2,7}$ P. Mueller,$^{1}$ T. P. O’Connor,$^{1}$ and J. T. Siugh$^{1,5}$

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(Received 3 March 2015; published 9 June 2015)

The radioactive radium-225 ($^{225}$Ra) atom is a favorable case to search for a permanent electric dipole moment. Because of its strong nuclear octupole deformation and large atomic mass, $^{225}$Ra is particularly sensitive to interactions in the nuclear medium that violate both time-reversal symmetry and parity. We have developed a cold-atom technique to study the spin precession of $^{225}$Ra atoms held in an optical dipole trap, and demonstrated the principle of this method by completing the first measurement of its atomic electric dipole moment, reaching an upper limit of $|d^{(225)} Ra| < 5.0 \times 10^{-23}$ e·cm (95% confidence).

DOI: 10.1103/PhysRevLett.114.233002

PACS numbers: 32.10.Dk, 11.30.Er, 24.80.+y, 37.10.Gh

The Argonne Ra-225 experiment: laser-cooled atoms!

MOT: 1000 atoms @ 40 µK
Dipole trap: 50 atoms at 50 µK

Our approach

- atomic EDM measurements with (non-radioactive) laser-cooled atoms
- find ways to improve sensitivity by using quantum phenomena
Choice of the atomic species

<table>
<thead>
<tr>
<th>Element</th>
<th>Period</th>
<th>Atomic Number</th>
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<td>3</td>
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<tr>
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<tr>
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<td>8</td>
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<tr>
<td>Fluorine</td>
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<td>Neon</td>
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<td>13</td>
</tr>
<tr>
<td>Silicon</td>
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<tr>
<td>Phosphorus</td>
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<td>15</td>
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<tr>
<td>Sulfur</td>
<td>16</td>
<td>16</td>
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<tr>
<td>Chlorine</td>
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<td>17</td>
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<td>19</td>
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<tr>
<td>Rubidium</td>
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<td>37</td>
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<tr>
<td>Strontium</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>Caesium</td>
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<td>55</td>
</tr>
<tr>
<td>Barium</td>
<td>6</td>
<td>56</td>
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<tr>
<td>Lanthanum</td>
<td>7</td>
<td>57-70</td>
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<tr>
<td>Actinium</td>
<td>6</td>
<td>89-102</td>
</tr>
</tbody>
</table>

EDM ~ $Z^3$
Mercury: a 2-electron atom

FHG laser system:

- Ti:Sa @ 740 nm
  - SHG to 370 nm: 7000 mW
  - SHG to 185 nm: 1200 mW
  - SHG to 370 nm: 10 mW

254 nm
1.3 MHz cooling transition

3P₁

185 nm
120 MHz

1S₀

266 nm
180 MHz clock transition

3P₀

DL @ 1016 nm
- 100 mW

TA @ 1016 nm
- 1200 mW

FA @ 1016 nm
- 10000 mW

SHG to 508 nm
- 3000 mW

SHG to 254 nm
- > 300 mW
The experimental setup

Atom beam

Magneto-optical trap

Dipole trap

Zeeman slowing

EDM measurement
Taking a classical experiment into the quantum world

2016 Seattle Hg-199 EDM experiment:
\[ |d_{\text{Hg}}| < 7.4 \times 10^{-30} \text{ e cm} \]

improve control:
- no spin decoherence from collisions with the walls
- no \( E \times v \) effect from movement of the atoms
- size reduces from 1 cm to a few 10 \( \mu \text{m} \): homogeneous fields
- in-vacuum electrodes: no leakage currents, much higher fields

improve sensitivity by at least a factor 10, conservative estimate:
\[ \delta d = 7 \times 10^{-31} \text{ e cm} \]

\[ \delta d = \frac{\hbar}{2E \sqrt{2N\tau T}} \]
- field \( E \): 30 keV on a 0.5-mm gap
- atom number \( N \): 10^8 atoms
- vacuum lifetime \( \tau \): 300 s
- measurement time \( T \): 3 months

evolve benefits of quantum nature:
- Heisenberg scaling through entanglement?
- state engineering (squeezing, decoherence-free subspace)?
- matter-wave interference?
### Expected sensitivity of the quMercury experiment

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

<table>
<thead>
<tr>
<th></th>
<th>Seattle (2016)</th>
<th>quMercury</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>first try</td>
</tr>
<tr>
<td>voltage</td>
<td>15 kV</td>
<td>10 kV</td>
</tr>
<tr>
<td>electrode gap</td>
<td>1.1 cm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>E-field</td>
<td>13.6 kV/cm</td>
<td>200 kV/cm</td>
</tr>
<tr>
<td>spin decoherence τ</td>
<td>100 s</td>
<td>100 s</td>
</tr>
<tr>
<td>atom number N</td>
<td>$2 \times 10^{14}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>measurement time T</td>
<td>10 months</td>
<td>3 months</td>
</tr>
<tr>
<td><strong>sensitivity δd</strong></td>
<td>$7.4 \times 10^{-30}$ e cm</td>
<td>$1.5 \times 10^{-28}$ e cm</td>
</tr>
<tr>
<td>comments</td>
<td>Nominal δd of 2 x 10^{-33} e cm not reached because of leakage currents.</td>
<td>Already six orders of magnitude better than Rn-221 and Ra-225 experiments in a dipole trap.</td>
</tr>
</tbody>
</table>
Expected sensitivity of the quMercury experiment
Current status...
Laser cooling is a powerful tool.
Laser cooling

Doppler shift + Zeeman shift = Zeeman slower
Magneto-optical trap

... but we can do better: sub-Doppler cooling

\[ T_D = \frac{\hbar \Gamma}{2k_B} \]
Narrow-line cooling

Hg Doppler temperature: 30 µK

\[ T_D = \frac{\hbar \Gamma}{2k_B} \]

\[ T_r = \frac{\hbar^2 k^2}{k_B m} \]
Trapping of Neutral Mercury Atoms and Prospects for Optical Lattice Clocks

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We report vapor-cell magneto-optical trapping of Hg isotopes on the 1S0−3P1 intercombination transition. Six abundant isotopes, including four bosons and two fermions, were trapped. Hg is the heaviest nonradioactive atom trapped so far, which enables sensitive atomic searches for “new physics” beyond the standard model. We propose an accurate optical lattice clock based on Hg and evaluate its systematic accuracy to be better than 10−18. Highly accurate and stable Hg-based clocks will provide a new avenue for the research of optical lattice clocks and the time variation of the fine-structure constant.

Katori group in 2008:
500,000 atoms of Hg-199 at 50 µK
Optical clocks with mercury

Katori group, RIKEN (Sr lattice clock)
Optical dipole traps

NP 2018:
Arthur Ashkin
optical tweezers

\[ U_{\text{dip}}(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3} \left( \frac{\Gamma}{\omega_0 - \omega} + \frac{\Gamma}{\omega_0 + \omega} \right) I(\mathbf{r}) \]

resonance frequency of the atom
frequency of the laser
Scattering properties are important (and unknown)

Evaporative cooling...

- is an efficient way to increase phase space density
- relies on re-thermalization of the atoms
- works only within a certain range of scattering properties

scattering cross section: $\sigma = 4\pi a_s^2$

<table>
<thead>
<tr>
<th>isotope</th>
<th>character</th>
<th>$I$</th>
<th>abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{166}\text{Hg}$</td>
<td>boson</td>
<td>0</td>
<td>0.15 %</td>
</tr>
<tr>
<td>$^{168}\text{Hg}$</td>
<td>boson</td>
<td>0</td>
<td>9.97 %</td>
</tr>
<tr>
<td>$^{199}\text{Hg}$</td>
<td>fermion</td>
<td>$\frac{1}{2}$</td>
<td>16.87 %</td>
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<tr>
<td>$^{200}\text{Hg}$</td>
<td>boson</td>
<td>0</td>
<td>23.10 %</td>
</tr>
<tr>
<td>$^{201}\text{Hg}$</td>
<td>fermion</td>
<td>$\frac{3}{2}$</td>
<td>13.18 %</td>
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<tr>
<td>$^{202}\text{Hg}$</td>
<td>boson</td>
<td>0</td>
<td>29.86 %</td>
</tr>
<tr>
<td>$^{204}\text{Hg}$</td>
<td>boson</td>
<td>0</td>
<td>6.87 %</td>
</tr>
</tbody>
</table>
Strontium, very similar to mercury.
Bose-Einstein condensation of Strontium

**loading of the dipole trap**

- $^{84}\text{Sr}$
- $t = 2\text{ s}$
- $t = 7\text{ s}$
- $t = 10\text{ s}$

**evaporation**

- Trap depth (μK)
- Atom number ($10^7$)
- Temperature (mK)

1.1 x $10^7$ atoms
Is there an advantage of quantum-degenerate atoms?

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