Progress toward measuring the e-EDM using the PbF molecule

Neil Shafer-Ray
July 2010

- Comparison of PbF to other e-EDM molecules.
- What our PbF e-EDM experiment might look like.
- Optical spectroscopy and detection of PbF (the development of \textit{pc-REMPI}).
- Microwave spectroscopy of PbF.
- How do we believe in an e-EDM measurement?
- A PROPOSED e-EDM-30 EXPERIMENT.
### Comparison of PbF to other e-EDM sensitive molecules

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*M Meyer, Bohn, PRA 78, 010502R  2008
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PbF is about a factor of 3 times less sensitive than HgF or ThO and 2 less than WC.

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PbF is a “g-2” e-EDM system. “g-2” implies g factor of ~0.04 “g” implies g factor of ~1

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*The ground-state of PbF is sensitive to an e-EDM*

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207PbF can be polarized by a field of as little as 0.2 kV/cm, ePbF requires ~5kV/cm

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#http://www-personal.umich.edu/~aehardt/research/WC.html
Outline of a possible measurement

polarize

detect

\[ \text{relative signal} \]

\[ 0.2 \, \mu G @ 10^{-27} \text{ e cm} \]

(10 mHz)
Outline of a possible measurement

polarize

B_{RF} E B

-B_{RF}

detect

PbF

\[ \text{E} \] \[ \text{B} \]

\[-1 \quad 0 \quad 1\]

\[ \text{relativ} \]

\[ 0.2 \mu G @ 10^{-27} \text{ e cm} \]

(10 mHz)
Outline of a possible measurement

polarize

B_RF

E

B

detect

PbF

\[ \text{relative signal} \]

\[ 0.2 \, \mu \text{G} \, @ \, 10^{-27} \, \text{e cm} \]

(10 mHz)
Outline of a possible measurement

PbF

B_{RF}

E

B

polarize

detect

\[ E \]

\[ B \]

\[ -1 \]

\[ 1 \]

\[ 0 \]

\[ 0.8 \]

\[ 0.6 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 0.2 \mu G \] @ \( 10^{-27} \) e cm

(10 mHz)
Outline of a possible measurement

polarize

\[ \text{signal} \]

\[ 0.2 \, \mu G \, @ \, 10^{-27} \, e \, \text{cm} \]

(10 mHz)
Outline of a possible measurement

Detect

PbF

Polarize

B_{RF} E B

-1 1 0

0.2 \mu G @ 10^{-27} e \text{ cm (10 mHz)}
Outline of a possible measurement

polarize

$E \quad B$

$B_{RF} \quad B_{RF}$

detect

$PbF$

Polarization

Relative signal

$0.2 \, \mu G \, @ \, 10^{-27} \, e \, cm$

$(10 \, mHz)$
Outline of a possible measurement

polarize

\[ E \quad B \]\n
\[ B_{RF} \quad B_{RF} \]

\[ \begin{array}{c}
-1 \\
0 \\
1 \\
\end{array} \]

\[ 0.2 \mu G @ 10^{-27} \text{e cm} \]

(10 mHz)
Outline of a possible measurement

polarize

B

E

B

B_{RF}

PbF

detect

0.2 \ \mu G \ @ \ 10^{-27} \ e \ cm

(10 \ mHz)
Outline of a possible measurement

E
polarize
B

$B_{RF}$

$E$

$B$

detect

$PbF$

$0.8$

$0.4$

$0.2$

$0$

$0.0$

$-100000$

$-50000$

$0$

$50000$

$100000$

$B(\mu G)$

relative signal

$0.2 \mu G @ 10^{-27} e cm$

$(10 mHz)$
The PbF e-EDM Project
2004-2009
Progress Report
Evolution of Sensitivity of the OU
Electron Electric Dipole Moment Experiment

- Anticipated by December 2010. (double resonance experiment.)
- Zeeman structure in Earth’s field resolved. Sensitive to magnetic moment of $^{19}$F [e].
- $^{19}$F hyperfine structure resolved, INVENTION OF pc-REMPI, highest resolution ever achieved in optical ionization of a molecule. [d]
- $^{207}$Pb hyperfine structure resolved [c]
- Rotational state resolution [b]
- Vibrational resolution, rotational structure, First REMPI of an e-EDM sensitive molecule. [a]

[b] Sivakumar, Phys. Rev. A, 77, 62508, 2008. (1+1+1 REMPI, $X_1 \rightarrow A \rightarrow D \rightarrow PbF^+$)
[c] McRaven, Phys. Rev. A, 78, 54502, 2008. (1+1+1 REMPI, $X_1 \rightarrow A \rightarrow D \rightarrow PbF^+$ injected seeded dye laser.)
[d] Sivakumar, Mol. Phys, March 12, 2010. (pc-REMPI, $X_1 \rightarrow A \rightarrow D \rightarrow PbF^+ + e^-$)
Multiphoton ionization of lead monofluoride resonantly enhanced by the $X_1^2\Pi_{1/2} \rightarrow B^2\Sigma_{1/2}$ transition

C. P. McRaven, P. Sivakumar, and N. E. Shafer-Ray*

The University of Oklahoma, 440 West Brooks Street, Norman, Oklahoma 73019, USA

(Received 5 December 2006; published 28 February 2007)

Equipment:
One 10 Hz, 10ns, Nd:YAG pumped dye laser

What learned:
Excitation cross sections, $IP = 7.54(1)$ eV

Limitation: Lifetime limited by B-state lifetime.
State-selective detection of the PbF molecule by doubly resonant multiphoton ionization

P. Sivakumar, C. P. McRaven, Dustin Combs, and N. E. Shafer-Ray
Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma,
440 West Brooks Street, Norman, Oklahoma 73019, USA

Victor Ezhev
Petersburg Nuclear Physics Institute, Gatchina, Petersburg District 188300, Russia
(Received 2 April 2008; published 10 June 2008)

Equipment:
Two 10 Hz, 10ns, Nd:YAG pumped dye lasers

What learned/Achieved:
Rotational/\(\Omega\)-doublet state resolution.
Spectroscopic constants of the D state.

Limitation: 0.1 cm\(^{-1}\) bandwidth laser: No hyperfine resolution.
Spectroscopic constants of the known electronic states of lead monofluoride

C. P. McRaven, P. Sivakumar, N. E. Shafer-Ray
Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, Norman, Oklahoma 73019, USA
Gregory E. Hall, Thomas J. Scanlan

<table>
<thead>
<tr>
<th>state</th>
<th>Experiment</th>
<th>Theorya</th>
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<tr>
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<tr>
<td>0</td>
<td>0</td>
<td>$^2\Pi^{1/2}$b</td>
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<td>B</td>
<td>35696.78</td>
<td>$^2\Sigma^{+}_{1/2}$c</td>
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<tr>
<td>C</td>
<td>38089</td>
<td>$3/2(2\Pi^{3/2})$d</td>
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<tr>
<td>D</td>
<td>43866.674</td>
<td>$1/2(2\Pi^{1/2})$d</td>
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<tr>
<td>E</td>
<td>45519.944</td>
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<td>F</td>
<td>47949.68</td>
<td>$3/2$d</td>
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aReference [9]

bReference [2]
cReference [4]
dThis work

$X_1 + h\nu \rightarrow A + h\nu \rightarrow \text{PbF}^* \rightarrow \text{PbF}^+$

Equipment:
Two 10 Hz, 10ns, Nd:YAG pumped dye lasers

What learned/Achieved:
Spectroscopic constants for D, E, and F states. Symmetry assignments. $X_1$-$X_2$-A mixed-state model, assumed since 1970’s is incorrect. Will affect e-EDM sensitivity by ~10%.
Experimental determination of the hyperfine constants of the $X_1$ and $A$ states of $^{207}\text{Pb}^{19}\text{F}$

C. P. McRaven, P. Sivakumar, and N. E. Shafer-Ray
Hommer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, Norman, Oklahoma 73019, USA
(Received 23 September 2008; published 17 November 2008)

Equipment:
Two 10 Hz, 10ns, Nd:YAG pumped dye lasers, one seeded with a diode laser.

What learned/Achieved:
Hyperfine structure of $^{207}\text{Pb}$ resolved.

Limit: 500 MHz bandwidth.

Unexpected closely spaced states of opposite parity! (267 MHz split.)
Error eventually traced to a 20-year-old phase error in theory.
PROBLEMS WITH REMPI Detection of PbF

1. First experiments driven by 10Hz, 10ns laser system. The beam is continuous. Effective duty cycle $\sim 10^{-4}$.

2. Pulsed beam implies resolution limited to 500MHz (we need about 80 MHz to resolve hyperfine states.)

**SOLUTION:** DEVELOP A NEW TYPE OF REMPI:

$p_{c}$-REMPI
CONVENTIONAL REMPI

V

Ion detector
CONVENTIONAL REMPI

V

Ion detector

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF

PbF+

PbF
CONVENTIONAL REMPI
CONVENTIONAL REMPI
CONVENTIONAL REMPI

DUTY CYCLE
$(L/V) / T_{rep}$
CONVENTIONAL REMPI WITH cw EXCITATION

V

Ion detector

DUTY CYCLE

\[ \frac{T_{\text{rep}}}{(L/V)} \]
CONVENTIONAL REMPI WITH cw EXCITATION
CONVENTIONAL REMPI WITH cw EXCITATION

DUTY CYCLE
\[ \frac{\tau}{T_{\text{rep}}} \sim 10^{-5} \]
pc-REMPI WITH cw EXCITATION

DUTY CYCLE
~1
pc-REMI REMPI Detection of PbF

476nm 76MHz 6ps 800 mW

436nm cw 10MHz

MCP PbF⁺ e⁻ MCP

multichannel scalar
RESEARCH ARTICLE

Pseudo-continuous resonance enhanced multiphoton ionisation: application to the determination of the hyperfine constants of $^{208}$Pb$^{19}$F

P. Sivakumar$^a$, C.P. McRaven$^a$, P.M. Rupasinghe$^a$, T.Zh. Yang$^a$, N.E. Shafer-Ray$^{ab}$, Trevor J. Sears$^b$ and Gregory E. Hall$^b$

$^a$Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, Norman, OK 73019-2061, USA;
$^b$Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

(Received 11 November 2009; final version received 11 December 2009)

Equipment:
Diode laser + 6 ps, 76 MHz OPO system.

What learned/Achieved:
Hyperfine structure of $^{19}$F resolved.
FULL hyperfine resolution.
Newly sensitive $pc$-REMPI technique demonstrated.

Lines predicted to ~1 MHz: TIME FOR COLLABORATION!
CONVENTIONAL REMPI

V

Ion detector
Fourier Transform Microwave Spectrometer: Pure rotational absorption spectrum of the $X_1$ state of PbF. (Collaborators Jens-Uwe Grabow, Richard Mawhorter Hanover Germany)
Zeeman-effect in PbF($X_1$) pure rotational spectra

$B = 0$

$\Delta M = 0$

$\Delta M = +/-1$

$\sim 3 \text{ kHz}$
Precise Characterization of the Ground $X_1$ State of $^{206}$Pb$^{19}$F, $^{207}$Pb$^{19}$F, and $^{208}$Pb$^{19}$F.

Richard Mawhorter, Benjamin Murphy
Department of Physics and Astronomy, Pomona College, Claremont CA 91711-6827

Trevor J. Sears
Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973 5000

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, USA

Lukas D. Alphie, Jens-Uwe Grabow
Liebniz Univ Hannover, Inst Phys Chem & Elektrochem, D-30167 Hannover, Germany

Equipment:
FT microwave spectrometer.

What learned/Achieved:
• Hyperfine constants,
• $g$-factors,
• energy levels modeled to $\sim 1\text{kHz}$ accuracy.
• combined with pc-REMPI measurement of dipole moment of PbF.

Pure rotational spectra of the $X_1$ state of PbF
Pure rotational spectra of the $X_1$ state of PbF

What learned/Achieved:
- Hyperfine constants,
- g-factors,
- energy levels modeled to $\sim 1$kHz accuracy.
- combined with pc-REMPI measurement of dipole moment of PbF.

Equipment:
FT microwave spectrometer.
How do we believe in an e-EDM?

polarize

\[ B_{RF} \]

detect

\[ PbF \]

State dependent shift!

\[ 0.2 \mu G @ 10^{-27} e cm \]

(10 mHz)
Experiment must be repeated at different fields, for different states, and for different systems (Cs, WC, ThO, ThF\textsuperscript{+}...)

\[ \text{\(^{208}\text{Pb}^{19}\text{F}\)} \]

\[ [J=1/2, p=-1, |M|=1, e-EDM shift] \]
Experiment must be repeated at different fields, for different states, and for different systems (Cs, WC, ThO, ThF⁺...)

$^{208}\text{Pb}^{19}\text{F}$

$[J=1/2, \, p=1, |M|=1, \, \text{e–EDM shift}]$
Experiment must be repeated at different fields, for different states, and for different systems (Cs, WC, ThO, ThF\(^+\) ...)

\[ ^{207}\text{Pb}^{19}\text{F} \]

\[ [J=1/2, p=1, |M|= 3/2, e-EDM shift] \]
Experiment must be repeated at different fields, for different states, and for different systems (Cs, WC, ThO, ThF\(^+\)…)

\[ ^{207}\text{Pb}^{19}\text{F} \]

\[ [J=1/2, p=1, |M|= 1/2, e^{-}\text{EDM shift}] \]

\[ \Delta U (\text{mHz}/10^{-27}\text{e cm}) \]

\[ E/(\text{kV/cm}) \]
The Group
The Group

Collaborators

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A proposed
e-EDM-30 Machine

If we could spend 10million (0.001 x LHC cost), what would we want?
NOT trapped cold neutral molecules.

Problems:

Geometric phase effects (for neutrals) limits coherence time to
\[ \sim 1 \text{ second} \times \left( \frac{T}{100 \mu K} \right)^{-2} \]


Interaction effects limit trap density / collection rates to \sim 1Hz.
**PROPOSAL**

An e-EDM beam line experiment using ground-state $g$-2 e-EDM molecules (PbF or WC)

Potential Minimum in $U = U_{\text{STARK}} + mg$ guides the beam. After ~2 meters, the PbF beam stops diverging!
The Proposed PbF Beam Line Experiment

FEATURES:
- 10 second coherence time, 100kHz data collection rate.

At $10^{-27} \text{ e cm}$, the (PbF) phase rotation is $40^\circ$.

The axial magnetic field needs to be $< 0.2 \mu \text{G}$.

$$10^{-28} \text{ e cm} / \sqrt{\text{sec}}$$