Atomic parity violation in Yb and Dy

D. Antypas

SSP 2018
Atomic Parity Violation at the Helmholtz-Institut Mainz

70  
Yb
Ytterbium 173.04

Dionysis Antypas
Anne Fabricant

66  
Dy
Dysprosium 162.50

Arijit Sharma
Lykourgos Bougas
Peter Leyser
Outline

• Background
• Motivations
• Yb experiment, new results & future
• Dy experiment
The weak interaction mixes atomic states of opposite nominal parity (s & p)
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\[ s \rightarrow s + i\varepsilon p; \quad p \rightarrow p + i\varepsilon s \]

\[ \varepsilon = \frac{\langle s \mid H_w \mid p \rangle}{\Delta E} \sim \frac{Z^3}{\Delta E} \quad - \text{the Bouchiat Law} \]

Atomic Parity Violation Enhancement:

- Heavy atoms (high Z)
- Small \( \Delta E \)
Atomic Parity Violation: Main processes

Nuclear-Spin Independent process

\[ Q_W \approx -N + Z \cdot (1 - 4 \sin^2 \theta_W) \]

- Probe of the Standard model parameter \( \theta_W \)
- Test of SM and constraints on physics beyond SM, including various "dark sector" scenarios

Main Nuclear-Spin Dependent process

Anapole moment-hadronic PV
Motivation I: anapole moment

Anapole moment:

- P-odd E/M moment from intranuclear PV
- Probe of weak meson-nucleon couplings (hadronic PV)

Safranova et al. arXiv:1710.01833
Motivation II: neutron skins

Weak charge: \( Q_W = -N + Z \cdot (1 - 4\sin^2 \theta_W) \)

What is probed however is:

\[
Q'_W = -N \cdot q_n + Z \cdot q_p (1 - 4\sin^2 \theta_W)
\]

\[
q_{n(p)} = \int f(r) \rho_{n(p)}(r) \, dr
\]

Neutron skin contribution between \(^{170}\text{Yb} - ^{176}\text{Yb}\) isotopes:

\[
\Delta Q_W / Q_W \sim 0.1\%
\]
Why PV with ytterbium

- Large PV effect (DeMille, 1995 - Tsigutkin et al, 2009)
Why PV with ytterbium

- **Large** PV effect (DeMille, 1995 - Tsigutkin et al, 2009)
- 7 stable isotopes (A=168, 170-174,176)

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<th>Isotope</th>
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<td>$^{174}\text{Yb}$</td>
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</tr>
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<td>16.1</td>
<td>5/2</td>
</tr>
<tr>
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<td>14.3</td>
<td>1/2</td>
</tr>
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<td>$^{170}\text{Yb}$</td>
<td>3.04</td>
<td>0</td>
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- PNC on chain of isotopes → neutron distributions
Why PV with ytterbium

- **Large** PV effect (DeMille, 1995 - Tsigutkin *et al*, 2009)
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- PNC on chain of isotopes $\rightarrow$ neutron distributions
- Two isotopes with nuclear spin $\rightarrow$ anapole moment
The Yb PV experiment

\[ \begin{align*}
R \propto & \left| A_{\text{Stark}} + A_{\text{PV}} \right|^2 \\
& \approx \beta^2 E^2 \sin^2 \theta + 2E_1 \beta E \cos \theta \sin \theta
\end{align*} \]

Reverse \( E \) (20 Hz) & \( \theta \) (0.2 Hz) and measure \( E l_{\text{PV}} / \beta \)
Observation of a Large Atomic Parity Violation Effect in Ytterbium

K. Tsigutkin,¹,* D. Dounas-Frazer,¹ A. Family,¹ J. E. Stalnaker,¹,† V. V. Yashchuk,² and D. Budker¹,³

Mean value: $39(4)_{stat}(5)_{syst}$ mV/cm, $|\xi| = 8.7 \pm 1.4 \times 10^{-10} ea_0$
Yb reincarnation in Mainz

New apparatus

• Newly built vacuum system
• More powerful and frequency stable laser system
• More precise control of fields applied in interaction region
• 20 times better SNR

Mainz Roadmap

• Verify expected isotopic dependence of PV (0.5% accuracy)
• Probe spin-dependent PV (sub-0.1 %)
• Neutron distributions (sub-0.1%)
Apparatus schematic
Early 2018 run in 4 spin-zero isotopes
First observation of isotopic variation of atomic PV

$$Q_W \approx - N + Z (1 - 4 \sin^2 \theta_W) \rightarrow 1\% \text{ change per neutron around } N=103$$

Observation: 0.96(15) \% change per neutron
Single isotope measurement uncertainties

<table>
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<th>Systematic uncertainties</th>
<th>Error (%)</th>
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<tr>
<td>Harmonics ratio calibration</td>
<td>0.22</td>
</tr>
<tr>
<td>Polarization angle</td>
<td>0.1</td>
</tr>
<tr>
<td>High-voltage measurements</td>
<td>0.06</td>
</tr>
<tr>
<td>Transition saturation correction</td>
<td>0.05 (0.09 for $^{170}$Yb)</td>
</tr>
<tr>
<td>Field-plate spacing</td>
<td>0.04</td>
</tr>
<tr>
<td>Photodetector response calibration</td>
<td>0.02</td>
</tr>
<tr>
<td>Stray fields &amp; field-misalignments</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Total systematic</strong></td>
<td><strong>0.26</strong></td>
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| Statistical uncertainty                                     | **0.42** (0.9 for $^{170}$Yb) |

**Total uncertainty**                                        **0.5** (0.9 for $^{170}$Yb)

Effect comparison **bonus:** decreased sensitivity to systematics
Yb PV measurement sensitivity
Next stop: anapole moment

\[ ^{171}\text{Yb}, I=1/2 \]

\[ ^3D_1 \]

\[ ^1S_0 \]

\[ F'=3/2 \]

\[ F'=1/2 \]

\[ 408 \text{ nm} \]

“Best guess” PV difference between \(^{171}\text{Yb} F'=3/2\) and \(F'=1/2 \sim 0.1\%\)

Need to boost SNR!

Yb sensitivity improvements (in progress)

Need x10 sensitivity enhancement for anapole, neutron skins

• Boost the Yb oven flux (x7 signal increase)
• Increase interaction region width (x2)
• Power build-up cavity mirrors upgrade (x2)
• Integrate longer...
Atomic PV in Dy

Dysprosium \{ \begin{itemize} 
\item Z=66 
\item 7 stable isotopes (A=156,158,160-164) 
\item $^{163}\text{Dy}$ & $^{161}\text{Dy}$ : $I=5/2$ (anapole moment) 
\end{itemize} \}
Atomic PV in Dy

Dysprosium \{ 
- Z=66
- 7 stable isotopes (A=156,158,160-164)
- $^{163}$Dy & $^{161}$Dy : I=5/2 (anapole moment)
\}

\[
\delta_W = \frac{\langle n'p|H_W|ns\rangle}{\Delta E} \sim Z^3
\]

Theory (1994)
$|H_W| = 70 \pm 40\text{Hz}$
V.A. Dzuba et al., PRA 50, 3812 (1994)

V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich (1986)
Enhancement of P- & T-odd effects in rear-earth atoms
Search for parity nonconservation in atomic dysprosium

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²Nuclear Science Division, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720
³Center for Beam Physics, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 2 June 1997)

Results of a search for parity nonconservation (PNC) in a pair of nearly degenerate opposite-parity states in atomic dysprosium are reported. The sensitivity to PNC mixing is enhanced in this system by the small energy separation between these levels, which can be crossed by applying an external magnetic field. The metastable odd-parity sublevel of the nearly crossed pair is first populated. A rapidly oscillating electric field is applied to mix this level with its even-parity partner. By observing time-resolved quantum beats between these sublevels, we look for interference between the Stark-induced mixing and the much smaller PNC mixing. To guard against possible systematic effects, reversals of the signs of the electric field, the magnetic field, and the decrossing of the sublevels are employed. We report a value of \(|H_w| = 2.3 \pm 2.9 \text{ (statistical)} \pm 0.7 \text{ (systematic)}\) Hz for the magnitude of the weak-interaction matrix element. A detailed discussion is given of the apparatus, data analysis, and systematic effects. [S1050-2947(97)02111-2]
Towards a sensitive search for variation of the fine-structure constant using radio-frequency $E1$ transitions in atomic dysprosium

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and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

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(Received 28 August 2003; published 12 February 2004)
Limit on the Temporal Variation of the Fine-Structure Constant Using Atomic Dysprosium

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2 Physics Division, Los Alamos National Laboratory, P-23, MS-H803, Los Alamos, New Mexico 87545, USA
3 Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 1 September 2006; published 26 January 2007)

University of California, Los Alamos National Laboratory, Physics Division, P-23, MS-H803, Los Alamos, New Mexico 87545, USA
(Received 28 August 2003; published 12 February 2004)
Investigation of the gravitational-potential dependence of the fine-structure constant using atomic dysprosium

S. J. Ferrell,¹ A. Cingöz,¹ A. Lapierre,² A.-T. Nguyen,³ N. Leefer,¹ D. Budker,¹,⁴ V. V. Flambaum,⁵,⁶ S. K. Lamoreaux,⁷ and J. R. Torgerson³
Transverse laser cooling of a thermal atomic beam of dysprosium

N. Leefer,1,* A. Cingöz,1,† B. Gerber-Siff,2 Arijit Sharma,3 J. R. Torgerson,4 and D. Budker1,5,‡
Transverse laser cooling of a thermal atomic beam of dysprosium

Limits on Violations of Lorentz Symmetry and the Einstein Equivalence Principle using Radio-Frequency Spectroscopy of Atomic Dysprosium

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C. Harabati, V. A. Dzuba, and V. V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia
(Received 14 March 2013; published 29 July 2013)
Transverse laser cooling of a thermal atomic beam of dysprosium

Limits on Violations of Lorentz Symmetry and the Einstein Equivalence Principle using Radio-Frequency Spectroscopy of Atomic Dysprosium

New Limits on Variation of the Fine-Structure Constant Using Atomic Dysprosium

Revived Dy Atomic PV experiment

**Improved theory (2010)**

\[ |H_W| = 4 \pm 4 \text{ Hz} \]

V. A. Dzuba & V. V. Flambaum,
PRA 81, 052515 (2010)

\[ \omega/(2\pi) \]

\[ \Delta \]

\[ g_F = 1.257 \]

\[ g_F = 1.112 \]

**Allowed Stark-PV interference**

\[ \hat{E} \cdot (B - B_{\text{crossing}}) \]

**Stark mixing amplitude**

Zeeman Crossing Spectroscopy

B-field (mG)
Dy setup upgrades & current status

- New apparatus
- CW laser sources
- Soon: Optical pumping to extreme $m_F$ states (x30 signal increase)
Mainz atomic PV crew

Dr. L. Bougas

Dr. A. Sharma

Prof. D. Budker

A. Frabricant

P. Leyser