Prospects for Atomic Parity Violation Experiments

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Outline

- A brief story of parity violation in atoms
- Mechanisms of APV
- Summary of measurements of atomic parity violation
- Prospects for new experiments on APV
- Berkeley experiment with Yb isotopes: present status and perspectives
Atomic PNC: important landmarks

- **1974 M.-A. & C. Bouchiat** \(Z^3\) enhancement \(\Rightarrow\) PNC observable in **heavy** atoms
- **1978-9** Novosibirsk, Berkeley discovery of PNC in OR(\textbf{Bi}) and Stark-interf.(\textbf{Tl})
- **1997** Boulder 0.35\% measurement, discovery of **anapole moment**

Prof. Ya. B. Zel’dovich
Sources of parity violation in atoms

$Z^0$-exchange between $e$ and nucleus

$\Rightarrow$ P-violating, T-conserving product of axial and vector currents

\[
\hat{h} = -\frac{G}{\sqrt{2}} \sum_N \left[ C_{1N} \bar{e} \gamma_\mu \gamma_5 e \bar{N} \gamma_\mu N + C_{2N} \bar{e} \gamma_\mu e \bar{N} \gamma_\mu \gamma_5 N \right]
\]

$C_{1n}$ is by a factor of 10 larger than $C_{1p}, C_{2N}$, leading to a dominance of the time-like nuclear spin-independent interaction $(A_e, V_N)$

A contribution to APV due to $Z^0$ exchange between electrons is suppressed by a factor $\sim 1000$ for heavy atoms.
Nuclear Spin-Independent (NSI) electron-nucleon interaction

NSI Hamiltonian in non-relativistic limit assuming equal proton and neutron densities $\rho(r)$ in the nucleus:

$$\hat{h}_w = -\frac{G}{2\sqrt{2}} Q_w \gamma_5 \rho(r)$$

The nuclear weak charge $Q_w$ to lowest order in the electroweak interaction is

$$Q_w = -N + Z(1 - 4\sin^2 \theta_w) \approx -N$$

The nuclear weak charge is protected from strong-interaction effects by conservation of the nuclear vector current. Thus, APV measurements allows for extracting weak couplings of the quarks and for searching for a new physics beyond SM

- NSI interaction gives the largest PNC effect compared to other mechanisms
- NSI interaction is scalar $\Rightarrow$ mixes only electron states of same angular momentum $j$
NSI interaction and particle physics implications

APV utilizes low-energy system and gives an access to the weak mixing angle, $\sin^2(\theta_W)$, at low-momentum transfer.

- J.L. Rosner, PRD 1999
- V.A. Dzuba, V.V. Flambaum, and O.P. Sushkov, PRA 1997
- J. Erler and P. Langacker, Ph.Lett. B 1999

APV experiments are sensitive to new tree-level physics at energies that cannot be currently achieved in colliders.

Limits of the mass and mixing angle for $Z'$ in $E_6$ models. The shaded area is excluded by the measurements of APV and from collider experiments.
NSI interaction and particle physics implications (continued)

Standard Model extensions, Oblique radiative corrections, Higgs sector.

Precision measurements of electroweak quantities constrain linear combinations of $S$ – isospin conserving, and $T$ – isospin breaking parameters.

Constraints of $S$ and $T$ from $\Gamma(Z^0)$ and from value of $\sin^2(\theta_W)$ as determined from forward-backward scattering asymmetries

APV experiments are not providing complimentary information to the high-energy experiments

Thus, the impact of the NSI APV is expected in constraining new tree-level physics rather than oblique radiative corrections

M.J. Ramsey-Musolf, PRC 1999
Isotope ratios and neutron distribution

The atomic theory errors can be excluded by taking ratios of APV measurements along an isotopic chain. While the atomic structure cancels in the isotope ratios, there is an enhanced sensitivity to the neutron distribution $\rho_n(r)$.

$$A_{PNC} = \delta(Q_W + Q^{\text{nuc}}_W)$$

$$Q^{\text{nuc}}_W = -N(q_n - 1) + Z(1 - 4\sin^2 \theta_W)(q_p - 1)$$

$$q_n = \int \rho_n(r)f(r)d^3r, \quad q_p = \int \rho_p(r)f(r)d^3r$$

$f(r)$ is the variation of the electron wave functions inside the nucleus normalized to $f(0)=1$.

$$R \equiv \frac{A_{PNC}(N')}{A_{PNC}(N)} \approx \frac{Q_W(N')}{Q_W(N)}[1 + \Delta q_n]$$

$$\Delta q_n \equiv q_n - q'_n$$

R is sensitive, in particular, to the difference in the neutron distributions.

This could be used to determine nuclear structure and test nuclear models complementing parity violating electron scattering measurements.
~$Z^3$ scaling of APV effects

Considering the electron wave functions in nonrelativistic limit and point-like nucleus the NSI Hamiltonian becomes:

$$\hat{h}_W = \frac{G}{4\sqrt{2}m_e} \left( \sigma \cdot p \, \delta^3(r) + \delta^3(r) \, \sigma \cdot p \right)$$

Since it is a local and a scalar operator it mixes only $s$ and $p_{1/2}$ states.

$$\langle p_{1/2} | \hat{h}_W | s \rangle \propto Z^2 Q_W$$

- $Z$ due to scaling of the probability of the valence electron to be at the nucleus
- $Z$ from the operator $p$, which near the nucleus (unscreened by electrons) $\propto Z$.
- $|Q_W| \approx N \sim Z$.

Strong enhancement of the APV effects in heavy atoms
Sources of NSD interaction

\[ \hat{h}_{NSD} = \frac{G \kappa}{\sqrt{2}} \gamma_0 \gamma I \rho(\vec{r}) \]

- **Anapole moment**
  \[ \kappa = \frac{K}{I+1} \kappa_A + \kappa_2 + \kappa_Q \]
  \[ K = (-1)^{I+1/2-l} (I+1/2) \]

- **Weak neutral current**
  \[ \kappa_A \approx 1.15 \cdot 10^{-3} A^{2/3} \mu_\alpha g_\alpha; \ A = N + Z; \]
  \[ \kappa_2 = \frac{1/2 - K}{I+1} C_{2\alpha} \]

- **Hyperfine correction to the weak neutral current**

\( \kappa_A \)-Anapole moment
\( \kappa_2 \)-Neutral currents
\( \kappa_Q \)-Radiative corrections
Anapole moment

In the nonrelativistic approximation PNC interaction of the valence nucleon with the nuclear core has the form:

\[ \hat{h}_A \sim \frac{G g_\alpha}{2\sqrt{2}} \frac{(\sigma p)}{m_p} n(r) \]

\[ n(r) \text{ is core density and } g_\alpha \text{ is dimensionless effective weak coupling constant for valence nucleon.} \]

- As a result, the spin \( \sigma \) acquires projection on the momentum \( p \) and forms **spin helix**
- Spin helix leads to the toroidal current. This current is proportional to the magnetic moment of the nucleon and to the cross section of the core.

\[ \kappa_A \approx 1.15 \cdot 10^{-3} A^{2/3} \mu_\alpha g_\alpha \]

**neutron** \( \mu_n = -1.2; g_n = -1 \)
**proton** \( \mu_p = 3.8; g_p = 5 \)

Anapole moment is bigger for nuclei with unpaired **proton**
Nuclear physics implication: weak meson coupling constants

There are 7 independent weak couplings for $\pi$-, $\rho$-, and $\omega$-mesons known as DDH constants. Proton and neutron couplings, $g_\alpha$, can be expressed in terms of 2 combinations of these constants:

\[ g_p = 8.0 \times 10^4 \left[ 70f_\pi - 19.5h^0 \right] \]
\[ g_n = 8.0 \times 10^4 \left[ -47f_\pi - 18.9h^0 \right] \]

\[ f_\pi \equiv f^1_\pi - 0.12h^1_\rho - 0.18h^1_\omega \]
\[ h^0 \equiv h^0_\rho + 0.7h^0_\omega \]

At present the values of the coupling constants are far from being reliably established. The projected measurement of the anapole moment in $^{173}$Yb should provide an important constraint.

Ask E158 SLAC group for an update after Jan. 2007
Signature of the weak interaction in atoms

\[ \hbar_{\text{NSI}} \text{ mixes } s_{1/2} \text{ and } p_{1/2} \text{ states of valence electron} \Rightarrow A_{\text{PV}} \text{ of dipole-forbidden transition.} \]

If \( A_{\text{PC}} \) is also induced, the amplitudes interfere.

\[ R \propto \left| A_{\text{PC}} + A_{\text{PV}} \right|^2 \approx A_{\text{PC}}^2 - 2A_{\text{PC}}A_{\text{PV}} + o(A_{\text{PV}}^2) \]

Interference

\[ A'_{\text{PC}} \]

E-field \iff Stark-effect \iff E1 PC-amplitude \( \propto E \) \iff E1-PNC interference term is odd in E

MUST:
Determine \( A_{\text{PC}} \) with high precision
Limit \( A'_{\text{PC}} \)
## Results of APV measurements

<table>
<thead>
<tr>
<th>Atom</th>
<th>Transition</th>
<th>Group</th>
<th>Year</th>
<th>Measurement</th>
<th>-Im(A&lt;sub&gt;PV&lt;/sub&gt;/M&lt;sub&gt;1&lt;/sub&gt;)</th>
<th>-Im(A&lt;sub&gt;PV&lt;/sub&gt;/β)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(10&lt;sup&gt;-8&lt;/sup&gt;)</td>
<td>(mV/cm)</td>
</tr>
<tr>
<td>209&lt;sup&gt;Bi&lt;/sup&gt;</td>
<td>^4S&lt;sub&gt;3/2&lt;/sub&gt;-^2D&lt;sub&gt;3/2&lt;/sub&gt;</td>
<td>Oxford</td>
<td>1991</td>
<td>10.12(20)</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>208&lt;sup&gt;Pb&lt;/sup&gt;</td>
<td>^3P&lt;sub&gt;0&lt;/sub&gt;-^3P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Seattle</td>
<td>1993</td>
<td>9.86(12)</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxford</td>
<td>1996</td>
<td>9.80(33)</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>205&lt;sup&gt;Tl&lt;/sup&gt;</td>
<td>^6P&lt;sub&gt;1/2&lt;/sub&gt;-^6P&lt;sub&gt;3/2&lt;/sub&gt;</td>
<td>Oxford</td>
<td>1995</td>
<td>15.68(45)</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seattle</td>
<td>1995</td>
<td>14.68(17)</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>133&lt;sup&gt;Cs&lt;/sup&gt;</td>
<td>^6S&lt;sub&gt;1/2&lt;/sub&gt;-^7S&lt;sub&gt;1/2&lt;/sub&gt;</td>
<td>Boulder</td>
<td>1988</td>
<td>1.576(34)</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boulder</td>
<td>1997</td>
<td>1.558(6)</td>
<td>0.35%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paris</td>
<td>2004</td>
<td>1.538(40)</td>
<td>2%</td>
<td></td>
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</table>

### Anapole moment:

* Measurements of APV with precision better than 5%

<table>
<thead>
<tr>
<th>Unpaired proton</th>
<th>133&lt;sup&gt;Cs&lt;/sup&gt; I=7/2</th>
<th>205&lt;sup&gt;Tl&lt;/sup&gt; I=1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_A \times 100 )</td>
<td>36.4(6.2)</td>
<td>-22(30)</td>
</tr>
</tbody>
</table>
# Ongoing experiments on APV

<table>
<thead>
<tr>
<th>Group</th>
<th>Atom/Ion</th>
<th>Goal</th>
<th>Advantages</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkeley</td>
<td>Yb isotopic chain</td>
<td>Nuclear structure, anapole moment</td>
<td>$A_{PNC}$ is a factor of 100 bigger than that of Cs. Seven isotopes.</td>
<td>Ongoing measurements</td>
</tr>
<tr>
<td>Seattle</td>
<td>Single trapped Ba$^+$ (Ra$^+$)</td>
<td>$Q_W$, anapole moment</td>
<td>Precise theory, $A_{PNC}$ is a factor of 20 bigger than that of Cs. Nine stable isotopes, $\Delta N=8$</td>
<td>Preliminary exps. on RF spectroscopy of trapped ions</td>
</tr>
<tr>
<td>Stony Brook, Legnaro, Yale, TRIUMF (Vancouver)</td>
<td>Cold Fr</td>
<td>Anapole moment</td>
<td>Precise theory, bigger effect than that of Cs, trapped atoms</td>
<td>Preliminary exps. on trapping of Fr</td>
</tr>
<tr>
<td>Yale</td>
<td>Diatomic molecules</td>
<td>Anapole moment, $C_2$</td>
<td>$A_{PNC}$ is enhanced due to proximity of the opposite parity levels. Level crossing</td>
<td>Development of theory and exp. techniques</td>
</tr>
</tbody>
</table>
By observing the $6s^2 \, ^1S_0 \rightarrow 6s6p \, ^3P_1$ 556 nm decay the pumping rate of the $6s^2 \, ^1S_0 \rightarrow 6s5d \, ^3D_1$ 408 nm transition is determined.

In addition, the population of $6s6p \, ^3P_0$ metastable level is probed by pumping the $6s6p \, ^3P_0 \rightarrow 6s7s \, ^3S_1$ 649 nm transition.

Proposed by D. DeMille, PRL 1995
Yb isotopes and abundances

Seven stable isotopes, two have non-zero spin

C.J. Bowers et al, PRA 1999
Rotational invariant and geometry of the Yb experiment

Rotational invariant to which the PV-Stark interference term is proportional is chosen so that \( \mathbf{E} \) is along the excitation light axis. This suppresses the interference between M1 and Stark amplitudes emphasizing the PV-Stark contribution.

Reversals:
- \( B \) – even
- \( E \) – odd

\[ \theta \rightarrow \theta \pm \pi/2 \] – odd

\[ |\beta| = 2.24(25) \times 10^{-8} \text{ e } a_0/(V/cm) \] – Stark transition polarizability (Measured by J. Stalnaker et al., PRA 2006)

\[ |\xi| = 1.08(24) \times 10^{-9} \text{ (QW/104) e } a_0/(V/cm) \] – Nuclear spin-independent PV amplitude (Calculations by Porsev et al, JETP Lett 1995; B. Das, PRA 1997)

\[
\begin{align*}
A^{q}_{\text{Stark}} &= i \beta (-1)^q \left( \frac{1}{\mathbf{E} \times \mathbf{E}} \right)_{-q} \langle j, m, 1, m' - m | j', m' \rangle \\
A^{q}_{\text{PNC}} &= i \xi (-1)^q \frac{r}{\mathbf{E} \times \mathbf{E}}_{-q} \langle j, m, 1, m' - m | j', m' \rangle; \quad q = m - m'
\end{align*}
\]
PV effect on line shapes: even isotopes

\[ E = (E,0,0) \]
\[ \mathbf{r} = (0,\sin \theta, \cos \theta) \]
\[ R^0 = \beta^2 E^2 \sin^2 \theta + 2E \beta \xi \sin \theta \cos \theta \]
\[ R^{\pm 1} = \frac{\beta^2 E^2}{2} \cos^2 \theta - E \beta \xi \sin \theta \cos \theta \]

176Yb

Reversing E-field

Rate modulation under the E-field reversal yields:

\[ \frac{R_{E+} - R_{E-}}{R_{E+} + R_{E-}} = \frac{2\xi}{\beta E} \]
PV effect on line shapes: odd isotopes

\[ \vec{E} = (E,0,0) \]
\[ \vec{\varepsilon} = (0,\sin \theta, \cos \theta) \]

\[ R_{\text{center}} = \frac{\beta_{FF} E^2}{6} (4 \sin^2 \theta + \cos^2 \theta) + E \beta_{FF} \xi' \sin \theta \cos \theta \]

\[ R_{\text{side}} = \frac{\beta_{FF} E^2}{2} \cos^2 \theta - E \beta_{FF} \xi' \sin \theta \cos \theta \]

\[ \xi' = \xi + \left< \mathbf{I} \cdot \mathbf{J} \right> \xi^{NSD} \]

171 Yb

- \( M' = 3/2 \)
- \( M' = -1/2 \)
- \( M' = 1/2 \)
- \( M' = 3/2 \)
- \( F' = 3/2 \)
- \( F = 1/2 \)

Reversing E-field

Intensity

Frequency

\( \xi^{NSD} \approx 10^{-12} \, \text{ea}_0 \) for odd Yb isotopes

\( \xi = 10^{-9} \, \text{ea}_0 \)

\( \xi' \) must be measured with 0.1% accuracy
Yb density in the beam $\sim 10^{10}$ cm$^{-3}$
Reversible E-field up to 15 kV/cm, spatial homogeneity 99%
Reversible B-field up to 100 G, homogeneity 99%

Light collection efficiency:
Interaction region: $\sim 0.2\%$ (556 nm)
Detection region: $\sim 25\%$
Optical system and control electronics

Light powers:
Ar\(^+\): 15W
Ti:Sapp (816 nm): 1W
Doubler (408 nm): 50 mW

PBC:
Confocal design, 25 cm;
Finesse \(\sim 4000\)
(upgrading to 40000)

Locking:
Pound-Drever-Hall technique
Doppler width and spectral resolution

Application of the atomic beam collimator allows to reduce the Doppler broadening by a factor of 10.

Spectral lines of closely neighboring isotopes can be clearly resolved.

Scanning over 408 nm line, observing 556 nm fluorescence at the interaction region.
Line shapes under the B-field

Under application of B-field line profiles demonstrate predicted shapes

Signal averaged over 100 scans
Scan rate = 1 Hz

Ready to collect data with E-field reversals
Systematic effects

\[ \vec{E} = (E, dE_y, dE_z) \]  
E-field inhomogeneity

\[ \vec{B} = (dB_x, dB_y, B_0) \]  
B-field inhomogeneity

\[ \vec{p} = (0, e^{idC} (\sin \theta + d \theta \cos \theta), \cos \theta - d \theta \sin \theta) \]  
Distortion of linear polarization of the light

\[ d \vec{k} \]  
Residual light propagation in the PBC

\[ M1 \sim 300 \xi \]

\[ A^q_{\Sigma} = (-1)^q \left( i \beta \left( \frac{\vec{r}}{E \times \vec{e}} \right)_{-q} + M1 \left( \frac{\vec{r}}{dk \times \vec{e}} \right)_{-q} + i \xi \frac{\vec{r}}{\vec{e}_q} \right) \langle F, m, l, m' - m \mid F', m' \rangle \]

Terms having same dependence on the leading E-field reversal and same polarization angle dependence as the Stark-PNC interference term must be limited

\[ \beta \frac{dB_x}{B} dE_y \ll \xi \]

\[ \beta dC dE_z \ll \xi \]

Required:

Non-reversing dB_x, dE_z \ll 1\%
Summary

• The program of measurements needed to understand the system is complete.

• It is now possible to proceed with confidence towards a first measurement of APV in Yb.

• The challenge will then be to refine the system to achieve the fractional precision needed to observe NSD effects.
## Timeline

**Berkeley experiment:**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
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<tbody>
<tr>
<td>½ yr</td>
<td>$A_{PV}$ enhancement, $A_{PV}:10%$</td>
</tr>
<tr>
<td>1 yr</td>
<td>$Q_W$ in single Yb isotope, $A_{PV}:1%$</td>
</tr>
<tr>
<td>1½ yr</td>
<td>$Q_W$ in chain of Yb isotopes, $A_{PV}:0.1%$</td>
</tr>
<tr>
<td>2 yr</td>
<td>Anapole moment</td>
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**ElectroWeak Workshop**