Parity and time reversal violation in atoms, molecules and nuclei and search for physics beyond the Standard Model

Victor Flambaum

Co-authors: I.Khriplovich, O.Sushkov, V.Dzuba, P.Silvestrov, N.Auerbach, Spevak, J.Ginges, M.Kuchiev, M.Kozlov, A.Brown, A.Derevianko, S.Porsev, J.Berengut, B.Roberts, A.Borschevsky, M.Ilias, K.Beloy, P.Schwerdtfeger
Overview

- Atoms as probes of fundamental interactions
  - atomic parity violation (APV)
    - nuclear weak charge
    - nuclear anapole moment
  - atomic electric dipole moments (EDMs)

- Enhancement in nuclei, atoms and molecules
- High-precision atomic many-body calculations
- QED radiative corrections in strong Coulomb field
- Cesium APV, test of Standard model
- EDM, test of Time reversal and CP violation theories
Atomic parity violation

- Dominated by Z-boson exchange between electrons and nucleons

\[ H = \frac{G}{\sqrt{2}} \left[ C_{1p} \bar{e} \gamma_\mu \gamma_5 e p \gamma^\mu + C_{1n} \bar{e} \gamma_\mu \gamma_5 e \bar{n} \gamma^\mu n \right] \]

Standard model tree-level couplings:

\[ C_{1p} = \frac{1}{2} \left(1 - 4 \sin^2 \theta_W\right); \quad C_{1n} = -\frac{1}{2} \]

- In atom with Z electrons and N neutrons obtain effective Hamiltonian parameterized by “nuclear weak charge” \( Q_W \)

\[ h_{PV} = \frac{G}{2\sqrt{2}} Q_W \rho(r) \gamma_5 \]

\[ Q_W = 2(NC_{1n} + ZC_{1p}) \approx -N + Z(1 - 4 \sin^2 \theta_W) \approx -N \]

- PV amplitude \( E_{PV} \propto Z^3 \)  

Discovered in 1978 Bi; Tl, Pb, Cs – accuracy 0.4-1%  
Our calculations in 1975-1989 Bi 11%, Pb 8%, Tl 3%, Cs 1%
High-precision atomic calculations

- **APV**

\[
E_{PV} (1 \rightarrow 2) = \sum_n \left[ \frac{\langle 2 | H_{PV} | n \rangle \langle n | D | 1 \rangle}{E_2 - E_n} + \frac{\langle 2 | D | nP \rangle \langle n | H_{PV} | 1 \rangle}{E_1 - E_n} \right] = \zeta Q_W
\]

- **Atomic EDM**

\[
d_{\text{atom}}(1) = 2 \sum_n \frac{\langle 1 | D_z | N \rangle \langle N | H_{PT} | 1 \rangle}{E_1 - E_N} = \zeta S
\]

\(H_{PV}\) is due to electron-nucleon P-odd interactions and nuclear anapole, \(H_{PT}\) is due to nucleon-nucleon, electron-nucleon PT-odd interactions, electron, proton or neutron EDM.

Atomic wave functions need to be good at all distances!

We check the quality of our wave functions by calculating:

- hyperfine structure constants and isotope shift
- energies
- E1 transition amplitudes

and comparing to measured values.

Also, estimates of higher order diagrams.
Ab initio methods of atomic calculations

<table>
<thead>
<tr>
<th>$N_{ve}$</th>
<th>Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Rel. Hartree-Fock+RPA</td>
<td>$\sim$ 10%</td>
</tr>
<tr>
<td>1</td>
<td>RHF+MBPT All-orders sums</td>
<td>0.1-1%</td>
</tr>
<tr>
<td>2-8</td>
<td>RHF+MBPT+CI</td>
<td>1-10%</td>
</tr>
<tr>
<td>2-15</td>
<td>Configuration interaction</td>
<td>10-20%</td>
</tr>
</tbody>
</table>

$N_{ve}$ - number of valence electrons

These methods cover all periodic table of elements
Tightly constrains possible new physics, e.g. mass of extra Z boson $M_{Z'} > 750 \text{ GeV}$.

Porsev, Derevianko 2009 Accuracy 0.27% . $Q_W - Q_W^{SM} = 0 \sigma$ We found 0.9% correction to this result which brings Porsev, Derevianko result into 0.1% agreement with our number. $Q_W - Q_W^{SM} = 1.5 \sigma$

$E_{PV} = -0.897(1 \pm 0.5\%) \times 10^{-11} \text{ ie}a_B(-Q_W/N)$

$\Rightarrow \quad Q_W - Q_W^{SM} = 1.1 \sigma$

$E_{PV}$ includes -0.8% shift due to strong-field QED self-energy / vertex corrections to weak matrix elements $W_{sp}$

$E_{PV} = \sum_p \frac{W_{sp}E_{1ps}}{E_s - E_p}$

[Kuchiev,Flambaum; Milstein,Sushkov,Terekhov]

A complete calculation of QED corrections to PV amplitude includes also

•QED corrections to energy levels and E1 amplitudes

[Flambaum,Ginges; Shabaev,Pachuki,Tupitsyn,Yerokhin]
Calculations and experiments in Cs analogues

Our calculations and calculations of other groups

Ba⁺

Fr, Ra⁺, Ac²⁺, Th³⁺  PNC effects 15 times larger

Experiments in Seattle (Ba⁺), TRIUMF (Fr), Groningen (Ra⁺)
PV: Chain of isotopes

Dzuba, Flambaum, Khriplovich

Rare-earth atoms:
- close opposite parity levels-enhancement
- Many stable isotopes

Ratio of PV effects gives ratio of weak charges. Uncertainty in atomic calculations cancels out. Experiments:
- Berkeley: Dy and Yb; PV amplitude 100 x Cs!
- Ra+ - Groningen, Fr- TRIUMF, (Ra Argonne?)
- Fortson, Pang, Wilets - neutron distribution problem

Test of Standard model or neutron distribution?

Brown, Derevianko, Flambaum 2009. Uncertainties in neutron distributions cancel in differences of PV effects in isotopes of the same element. Measurements of ratios of PV effects in isotopic chain can compete with other tests of Standard model!
Nuclear anapole moment

- Source of nuclear spin-dependent PV effects in atoms
- Nuclear magnetic multipole violating parity
- Arises due to parity violation inside the nucleus
- Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

\[ \tau_a = e \alpha \cdot A \propto \kappa_a \alpha \cdot \rho(r), \quad \kappa_a \propto A^{2/3} \]

[Flambaum, Khriplovich, Sushkov]

\[ E_{PV} \propto Z^2 A^{2/3} \] measured as difference of PV effects for transitions between hyperfine components

Cs: |6s, F=3> - |7s, F'=4> and |6s, F'=4> - |7s, F=3>

Probe of weak nuclear forces via atomic experiments!
Nuclear anapole moment is produced by PV nuclear forces. Measurements +our calculations give the strength constant g.

- Boulder Cs: \( g = 6(1) \) in units of Fermi constant
- Seattle Tl: \( g = -2(3) \)

New accurate calculations Flambaum, Hanhart; Haxton, Liu, Ramsey-Musolf; Auerbach, Brown; Dmitriev, Khriplovich, Telitsin: problem remains.

Experiments and proposals: Fr (TRIUMF), \( 10^3 \) enhancement in Ra atom due to close opposite parity state; Dy, Yb, ... (Berkeley)
Enhancement of nuclear anapole effects in molecules

\(10^5\) enhancement of the anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity. Theorem: only nuclear-spin-dependent (anapole) contribution to PV is enhanced (Labzovsky; Sushkov, Flambaum 1978). Weak charge can not mix opposite parity rotational levels and \(\Lambda\)-doublet.

\(\Omega=1/2\) terms: \(\Sigma_{1/2}, \Pi_{1/2}\). Heavy molecules, effect \(Z^2 A^{2/3} R(Z\alpha)\)

YbF, BaF, PbF, LuS, LuO, LaS, LaO, HgF,… Cl, Br, I,… BiO, BiS,…

Cancellation between hyperfine and rotational intervals-enhancement. Interval between the opposite parity levels may be reduced to zero by magnetic field – further enhancement.

Molecular experiments: Yale, Groningen, NWU.

**New calculations** for many molecules and molecular ions: Borschevsky, Ilias, Beloy, Dzuba, Flambaum, Schwerdtfeger 2012
Accurate molecular calculations

- RaF: T.A.Isaev, S. Hoekstra, R. Berger.

Experimental proposals:
- DeMille et al
Atomic electric dipole moments

- Electric dipole moments violate parity (P) and time-reversal (T)

- T-violation \(\equiv\) CP-violation by CPT theorem

CP violation

- Observed in \(K^0, B^0\)
- Accommodated in SM as a single phase in the quark-mixing matrix (Kobayashi-Maskawa mechanism)

However, not enough CP-violation in SM to generate enough matter-antimatter asymmetry of Universe!

\(\Rightarrow\) Must be some non-SM CP-violation
• Excellent way to search for new sources of CP-violation is by measuring EDMs
  - SM EDMs are hugely suppressed
    → Theories that go beyond the SM predict EDMs that are many orders of magnitude larger!

<table>
<thead>
<tr>
<th>Theory</th>
<th>$d_e$ (e cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Mdl.</td>
<td>$&lt; 10^{-38}$</td>
</tr>
<tr>
<td>SUSY</td>
<td>$10^{-28} - 10^{-26}$</td>
</tr>
<tr>
<td>Multi-Higgs</td>
<td>$10^{-28} - 10^{-26}$</td>
</tr>
<tr>
<td>Left-right</td>
<td>$10^{-28} - 10^{-26}$</td>
</tr>
</tbody>
</table>

e.g. electron EDM

Best limit (90% c.l.): $|d_e| < 1.6 \times 10^{-27}$ e cm

• Atomic EDMs $d_{\text{atom}} \propto Z^3$

  Sensitive probe of physics beyond the Standard Model!
Nuclear EDM:
T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM
Sushkov, Flambaum, Khriplovich
1984
T, P-odd NN interaction

Khriplovich, Sushkov, Flambaum 1984, 1986

- Calculations of nuclear EDM and Schiff moments
- Calculations of atomic EDM
- Calculation of T, P-odd $\pi$ NN and nucleon-nucleon interaction in the Standard model.
  NN interaction strength $0.3 \times 10^{-8}$ G. Current limit from atomic EDM $10^{-4}$ G.
- We need physics beyond Standard model
- Or new enhanced effects.
Atomic EDMs

Best limits

\[ |d^{(199}\text{Hg})| < 3 \times 10^{-29} \text{ e cm} \]
(95% c.l., Seattle, 2009)

\[ |d^{(205}\text{Tl})| < 9.6 \times 10^{-25} \text{ e cm} \]
(90% c.l., Berkeley, 2002)

\[ |d(n)| < 2.9 \times 10^{-26} \text{ e cm} \]
(90% c.l., Grenoble, 2006)

Leading mechanisms for EDM generation

- fundamental CP-violating phases
- neutron EDM
- EDMs of diamagnetic systems (Hg,Ra)
- EDMs of paramagnetic systems (Tl)

\[ \psi = + + \beta_{PT} + \]

\[ |\psi|^2 = \]

\[ \bar{N}N\bar{N}N \]

Schiff moment

quark/lepton level
nucleon level
nuclear level
atomic level
Screening of external electric field in atoms—our calculation
Nuclear EDM-screening: $d_N \ E_N$

- Schiff theorem: $E_N = 0$, neutral systems
- Extension for ions and molecules: Flambaum, Kozlov

Ion acceleration $a = Z_i \ eE/M$
Nucleus acceleration $a = Z \ eE_N/M$

$$E_N = E \ \frac{Z_i}{Z}$$

In molecules screening is stronger:

$$a = Z_i \ eE/(M + m), \quad E_N = E \ (Z_i/Z)(M/(M + m))$$

Schiff moment dominates in molecules!
Diamagnetic atoms and molecules

Source-nuclear Schiff moment

SM appears when screening of external electric field by atomic electrons is taken into account.

Nuclear T,P-odd moments:

- **EDM** – non-observable due to total screening (Schiff theorem)

Nuclear electrostatic potential with screening (our 1984 calculation following ideas of Schiff and Sandars):

\[
\varphi(R) = \int \frac{e\rho(r)}{|R - r|} d^3r + \frac{1}{Z} (d \cdot \nabla) \int \frac{\rho(r)}{|R - r|} d^3r
\]

\( d \) is nuclear EDM, the term with \( d \) is the electron screening term \( \varphi(R) \) in multipole expansion is reduced to

\[
\varphi(R) = 4\pi S \cdot \nabla \delta(R)
\]

where

\[
S = \frac{e}{10} \left[ \langle r^2 r \rangle - \frac{5}{3Z} \langle r^2 \rangle \langle r \rangle \right]
\]

is **Schiff moment**.

This expression is not suitable for relativistic calculations.
Flambaum, Ginges: 
\[ L = S(1 - c Z^2 \alpha^2) \]

\[ \phi(R) = -\frac{3L \cdot R}{B} \rho(R) \]

where

\[ B = \int \rho(R) R^4 dR \]

This potential has no singularities and may be used in relativistic calculations. SM electric field polarizes atom and produces EDM. Calculations of nuclear SM: Sushkov, Flambaum, Khriplovich; Brown et al, Flambaum et al, Dmitriev et al, Auerbach et al, Engel et al, Liu et al, Sen’kov et al, Ban et al. Atomic EDM: Sushkov, Flambaum, Khriplovich; Dzuba, Flambaum, Ginges, Kozlov. Best limits from Hg EDM measurement in Seattle - Crucial test of modern theories of CP violation (supersymmetry, etc.)
Atomic EDM induced by Schiff
moment rapidly increases with
nuclear charge, $Z^2 R (Z^\alpha)$

- We performed accurate many-body
calculations for heavy atoms: Xe, Yb, Hg,
  Rn, Ra; Measurements for Xe (Seattle, Ann
  Arbor) and Hg (Seattle).

- In molecules there is an additional
  enhancement suggested by Sandars: internal
  electric field of polarised molecule is orders of
  magnitude larger than applied external field
Calculations and measurements in TIF (Hinds)
Nuclear enhancement
Auerbach, Flambaum, Spevak 1996

The strongest enhancement is due to octupole deformation (Rn, Ra, Fr, ...)

Intrinsic Schiff moment:

\[ S_{\text{intr}} \approx eZR^3_N \frac{9\beta_2\beta_3}{20\pi\sqrt{35}} \]

- \( \beta_2 \approx 0.2 \) - quadrupole deformation
- \( \beta_3 \approx 0.1 \) - octupole deformation

No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame
However, in laboratory frame \( S=d=0 \) due to rotation
In the absence of T,P-odd forces: doublet (+) and (-)

\[ \Psi = \frac{1}{\sqrt{2}} \left( |IMK\rangle + |IM - K\rangle \right) \]

and \( \langle n \rangle = 0 \)

\[ K = (I \cdot n) \]

T,P-odd mixing (\( \beta \)) with opposite parity state (-) of doublet:

\[ \Psi = \frac{1}{\sqrt{2}} \left[ (1 + \beta)|IMK\rangle + (1 - \beta)|IM - K\rangle \right] \]

and \( \langle n \rangle \propto \beta I \)

EDM and Schiff moment

\[ \langle d \rangle, \langle S \rangle \propto \langle n \rangle \propto \beta I \]
Simple estimate (Auerbach, Flambaum, Spevak):

\[ S_{\text{lab}} \propto \frac{\langle + | H_{TP} | - \rangle}{E_+ - E_-} S_{\text{body}} \]

Two factors of enhancement:
1. Large collective moment in the body frame
2. Small energy interval \((E_+ - E_-)\), 0.05 \(\text{MeV}\) instead of 8 \(\text{MeV}\)

\[ S \approx 0.05 e^2 \beta_2 \beta_3^2 Z A^{2/3} \eta_0^3 \frac{\text{eV}}{E_+ - E_-} \approx 700 \times 10^{-8} \eta \text{efm}^3 \approx 500 S(\text{Hg}) \]

\(^{225}\text{Ra}, ^{223}\text{Rn}, \text{Fr}..., -100\text{-}1000 \text{ times enhancement}\)

Engel, Friar, Hayes (2000); Flambaum, Zelevinsky (2003):
Static octupole deformation is not essential, nuclei with soft octupole vibrations also have the enhancement.

Nature 2013 Experiment: Octupole deformation in \(^{224}\text{Ra}, ^{220}\text{Rn}, \text{Fr}..., \text{Hg}\)
# EDMs of atoms of experimental interest

<table>
<thead>
<tr>
<th>Z</th>
<th>Atom</th>
<th>([S/(e \text{fm}^3)]e \text{cm})</th>
<th>([10^{-25} \eta] e \text{cm})</th>
<th>Expt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>(^3\text{He})</td>
<td>0.00008</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>(^{129}\text{Xe})</td>
<td>0.38</td>
<td>0.7</td>
<td>Seattle, Ann Arbor, Princeton</td>
</tr>
<tr>
<td>70</td>
<td>(^{171}\text{Yb})</td>
<td>-1.9</td>
<td>3</td>
<td>Bangalore, Kyoto</td>
</tr>
<tr>
<td>80</td>
<td>(^{199}\text{Hg})</td>
<td>-2.8</td>
<td>4</td>
<td>Seattle</td>
</tr>
<tr>
<td>86</td>
<td>(^{223}\text{Rn})</td>
<td>3.3</td>
<td>3300</td>
<td>TRIUMF</td>
</tr>
<tr>
<td>88</td>
<td>(^{225}\text{Ra})</td>
<td>-8.2</td>
<td>2500</td>
<td>Argonne, KVI</td>
</tr>
<tr>
<td>88</td>
<td>(^{223}\text{Ra})</td>
<td>-8.2</td>
<td>3400</td>
<td></td>
</tr>
</tbody>
</table>

Standard Model $\eta = 0.3 \times 10^{-8}$  

$d_n = 5 \times 10^{-24} e \text{cm} \eta$,  

$d(^{199}\text{Hg})/d_n = 10^{-1}$
RaO molecule

Enhancement factors
• Biggest Schiff moment
• Highest nuclear charge
• Close rotational levels of opposite parity (strong internal electric field)

Largest T,P-odd nuclear spin-axis interaction $\kappa(l\ n)$, $\text{RaO} = 200$ TlF

Flambaum 2008; Kudashov, Petrov, Skripnikov, Mosyagin, Titov, Flambaum 2013
Limits on the P,T-violating parameters in the hadronic sector extracted from Hg compared to the best limits from other experiments

Best limit on atomic EDM (Seattle, 2001; 7 times better in 2009):

\[ d(^{199} \text{Hg}) = -(1.06 \pm 0.49 \pm 0.40) \times 10^{-28} \text{e}\cdot\text{cm} \]

<table>
<thead>
<tr>
<th>P,T-odd term</th>
<th>Value</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron EDM ( d_n ) [10^{-26} \text{e cm}]</td>
<td>(17 ± 8 ± 6) (1.9 ± 5.4) (2.6 ± 4.0 ± 1.6)</td>
<td>Hg n n Seattle, 2001 ILL, 1999 PNPI, 1996</td>
</tr>
<tr>
<td>proton EDM ( d_p ) [10^{-24} \text{e cm}]</td>
<td>(1.7 ± 0.8 ± 0.6) (17 ± 28)</td>
<td>Hg TIF Seattle, 2001 Yale, 1991</td>
</tr>
<tr>
<td>( \eta_{np} ) ( \frac{G}{\sqrt{2}} ) ( \bar{p}p\gamma_5 n )</td>
<td>( \eta_{np} = (2.7 \pm 1.3 \pm 1.0) \times 10^{-4} )</td>
<td>Hg Seattle, 2001</td>
</tr>
<tr>
<td>QCD phase ( \theta ) [10^{-10}]</td>
<td>(1.1 ± 0.5 ± 0.4) (1.6 ± 4.5) (2.2 ± 3.3 ± 1.3)</td>
<td>Hg n n Seattle, 2001 ILL, 1999 PNPI, 1996</td>
</tr>
</tbody>
</table>
Atomic EDMs

Best limits

- $|d^{(199\text{Hg})}| < 3 \times 10^{-29} \, \text{e cm}$
  (95% c.l., Seattle, 2009)

- $|d^{(205\text{Tl})}| < 9.6 \times 10^{-25} \, \text{e cm}$
  (90% c.l., Berkeley, 2002)

- $|d(n)| < 2.9 \times 10^{-26} \, \text{e cm}$
  (90% c.l., Grenoble, 2006)

Leading mechanisms for EDM generation

- fundamental CP-violating phases
  - $d_q$, $\tilde{d}_q$, $\theta$
  - $d_e$

- neutron EDM
  - $\tilde{N}N\tilde{N}N$

- EDMs of diamagnetic systems (Hg,Ra)

- EDMs of paramagnetic systems (Tl)

- quark/lepton level
- nucleon level
- nuclear level
- atomic level

$$\psi = + + \beta_{PT}$$

$$|\psi|^2 =$$
Enhancement of electron EDM

- Sandars: atomic EDM induced by interaction of electron EDM with atomic electric field increases as $Z^3$. Enhancement $>100$
- Flambaum: Enhancement factor in atoms $3 Z^3 \alpha^2 R(Z\alpha)$
- Numerical calculations in atoms: Tl enhancement $d(Tl) = -582\, d_e$
  - Experiment – Berkeley; Cs, Fr, Xe*,
- Molecules – close rotational levels, huge enhancement of electron EDM: $Z^3 \alpha^2 R(Z\alpha) M/m_e$ Sushkov, Flambaum 1978
  - $\Omega = 1/2$ $10^7$ YbF London, best limit on $d_e$
  - $\Omega = 1$ $10^{10}$ PbO, ThO Yale, Harvard
    - HfF+ ThF+ Boulder

Weak electric field is sufficient to polarise the molecule. Molecular electric field is several orders of magnitude larger than external field (Sandars)
Extra enhancement in excited states: Ra

\[ d_{\text{atom}}(1) = 2 \sum_{N} \frac{\langle 1 | D_{z} | N \rangle \langle N | H_{\text{PT}} | 1 \rangle}{E_{1} - E_{N}} \]

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels
  
  [Flambaum; Dzuba, Flambaum, Ginges]

\[ d(3D_{2}) \sim 10^{5} \times d(\text{Hg}) \]

Experiment Groningen

\[ E_{\text{PV}}(1S_{0} - 3D_{1,2}) \sim 100 \times E_{\text{PV}}(\text{Cs}) \]

Comparison of even Ra isotopes

Good to study anapole moment:
- Strongly enhanced \( (E_{\text{PV}} \sim 10^{3} E_{\text{PV}}(\text{Cs})) \)
- \( Q_{W} \) does not contribute (\( \Delta J = 1 \))
- PV in optical or microwave transition
Atomic EDM produced by electron-nucleus $T,P$-odd interaction

We performed accurate many-body calculations in diamagnetic and paramagnetic atoms and molecules
Summary

- Precision atomic physics can be used to probe fundamental interactions
  - unique test of the standard model through APV, now agreement
  - Nuclear anapole, probe of PV weak nuclear forces (in APV)
  - EDM, unique sensitivity to physics beyond the standard model. 1-3 orders improvement may be enough to reject or confirm all popular models of CP violation, e.g. supersymmetric models

- A new generation of experiments with enhanced effects is underway in atoms, diatomic molecules, and solids
Cs PNC: conclusion and future directions

• Cs PNC is still in perfect agreement with the standard model
• Theoretical uncertainty is now dominated by correlations (0.5%)
• Improvement in precision for correlation calculations is important. Derevianko aiming for 0.1% in Cs.
• Similar measurements and calculations can be done for Fr, Ba+, Ra+
Precision atomic physics can be used to probe fundamental interactions

- EDMs (existing): Xe, Tl, Hg
- EDMs (new): Xe, Ra, Yb, Rn
- EDM and APV in metastable states: Ra, Rare Earth
- Nuclear anapole: Cs, Tl, Fr, Ra, Rare Earth
- APV \( (Q_W) \): Cs, Fr, Ba+, Ra+

Atomic theory provides reliable interpretation of the measurements
Atoms as probes of fundamental interactions

• T,P and P-odd effects in atoms are strongly enhanced:
  • $Z^3$ or $Z^2$ electron structure enhancement (universal)
  • Nuclear enhancement (mostly for non-spherical nuclei)
    • Close levels of opposite parity
    • Collective enhancement
    • Octupole deformation
  • Close atomic levels of opposite parity (mostly for excited states)

• A wide variety of effects can be studied:
  Schiff moment, MQM, nucleon EDM, $e^-$ EDM via atomic EDM
  $Q_W$, Anapole moment via $E(PNC)$ amplitude
Nuclear anapole moment
• Source of nuclear spin-dependent PV effects in atoms
• Nuclear magnetic multipole violating parity
• Arises due to parity violation inside the nucleus

Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

\[ h_a = e \alpha \cdot A \propto \kappa_a \alpha \cdot \rho(r), \quad \kappa_a \propto A^{2/3} \]

[Flambaum,Khriplovich,Sushkov]

\( E_{PV} \propto Z^2 A^{2/3} \) measured as difference of PV effects for transitions between hyperfine components

• Boulder Cs: \( g = 6(1) \) (in units of Fermi constant)
• Seattle Tl: \( g = -2(3) \)
Flambaum, Ginges, 2002:

\[
\varphi(R) = -\frac{3S \cdot R}{B} \rho(R)
\]

where

\[
B = \int \rho(R) R^4 dR
\]

Electric field induced by T,P-odd nuclear forces which influence proton charge density. This potential has no singularities and may be used in relativistic calculations. Schiff moment electric field polarizes atom and produce EDM.

Relativistic corrections originating from electron wave functions can be incorporated into Local Dipole Moment (L).

\[
L = \sum_{k=1}^{\infty} S_k
\]

\[
\varphi(R) = 4\pi L \cdot \nabla \delta(R)
\]
Schiff moment

SM appears when screening of external electric field by atomic electrons is taken into account.

Nuclear T,P-odd moments:

- **EDM** – non-observable due to total screening
- **Electric octupole moment** – modified by screening
- **Magnetic quadrupole moment** – not significantly affected

Nuclear electrostatic potential with screening:

\[
\varphi(R) = \int \frac{e \rho(r)}{|R-r|} d^3r + \frac{1}{Z} (d \cdot \nabla) \int \frac{\rho(r)}{|R-r|} d^3r
\]

\(d\) is nuclear EDM, the term with \(d\) is the electron screening term \(\varphi(R)\) in multipole expansion is reduced to

\[
\varphi(R) = 4\pi S \cdot \nabla \delta(R)
\]

where

\[
S = \frac{e}{10} \left[ \langle r^2 r \rangle - \frac{5}{3Z} \langle r^2 \rangle \langle r \rangle \right]
\]

is Schiff moment.

This expression is not suitable for relativistic calculations.
Extra enhancement in excited states: Ra

\[ d_{\text{atom}}(1) = 2 \sum_{N} \frac{\langle 1 | D_z | N \rangle \langle N | H_{\text{PT}} | 1 \rangle}{E_1 - E_N} \]

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels
  
  [Flambaum; Dzuba, Flambaum, Ginges]

\[ d(3D_2) \sim 10^5 \times d(\text{Hg}) \]

\[ E_{\text{PV}}(1S_0-3D_{1,2}) \sim 100 \times E_{\text{PV}}(\text{Cs}) \]
Matrix elements: \( \langle \psi_a | h + \delta V + \delta \Sigma | \psi_b \rangle \)

\( \psi_{a,b} \) - Brueckner orbitals: \((H^{HF} - \varepsilon_a + \Sigma) \psi_a = 0\)

\( h \) - External field

\( \langle \psi_a | \delta V | \psi_b \rangle \) - Core polarization

\( \langle \psi_a | \delta \Sigma | \psi_b \rangle \) - Structure radiation

Example: PNC \( E(6s-7s) \) in \(^{133}\)Cs [ \( 10^{-11} \)ea\( B (-Q_{W/N}) \)]

\( E_{PNC} = 0.91(1) \) (Dzuba, Sushkov, Flambaum, 1989)

\( E_{PNC} = 0.904(5) \) (Dzuba, Flambaum, Ginges, 2002)
**Close states of opposite parity in Rare-Earth atoms**

<table>
<thead>
<tr>
<th>Z</th>
<th>Atom</th>
<th>Even</th>
<th>Odd</th>
<th>$\Delta E$ [cm$^{-1}$]</th>
<th>$\Delta J$</th>
<th>What</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>Nd II</td>
<td>$^6G_{11/2}$</td>
<td>$^6L_{13/2}$</td>
<td>8</td>
<td>1</td>
<td>S,M</td>
</tr>
<tr>
<td>62</td>
<td>SM I</td>
<td>$4f^65d6s$</td>
<td>$4f^66s6p$</td>
<td>5</td>
<td>0</td>
<td>S,E,M</td>
</tr>
<tr>
<td>62</td>
<td>SM I</td>
<td>$^7D_4$</td>
<td>$^9G_5$</td>
<td>10</td>
<td>1</td>
<td>S,M</td>
</tr>
<tr>
<td>64</td>
<td>Gd I</td>
<td>$^{11}F_5$</td>
<td>$^9P_3$</td>
<td>0</td>
<td>2</td>
<td>A,M</td>
</tr>
<tr>
<td>66</td>
<td>Dy I</td>
<td>$4f^{10}5d6s$</td>
<td>$4f^{10}6s6p$</td>
<td>1</td>
<td>1</td>
<td>A,S,M</td>
</tr>
<tr>
<td>66</td>
<td>Dy I</td>
<td>$4f^{10}5d6s$</td>
<td>$4f^{9}5d^26s$</td>
<td>0</td>
<td>0</td>
<td>A,E,S,M</td>
</tr>
<tr>
<td>67</td>
<td>Ho I</td>
<td>$^8K_{21/2}$</td>
<td>$4f^{10}6s^26p$</td>
<td>10</td>
<td>1</td>
<td>S,M</td>
</tr>
</tbody>
</table>

$S =$ Schiff Moment, $A =$ Anapole moment, $E =$ Electron EDM, $M =$ Magnetic quadrupole moment
Radiative potential for QED

\[ \Phi_{\text{rad}}(r) = \Phi_U(r) + \Phi_g(r) + \Phi_f(r) + \Phi_l(r) + \frac{2}{3} \Phi_{\text{WC}}^{\text{simple}}(r) \]

\[ \phi_g(r) + \phi_f(r) + \phi_l(r) = \]

\[ \phi_U(r) + \frac{2}{3} \phi_{\text{WC}}^{\text{simple}}(r) = \]

\( \Phi_g(r) \) - magnetic formfactor
\( \Phi_f(r) \) - electric formfactor
\( \Phi_l(r) \) - low energy electric formfactor
\( \Phi_U(r) \) - Uehling potential
\( \Phi_{\text{WC}}(r) \) - Wichmann-Kroll potential

\( \Phi_f(r) \) and \( \Phi_l(r) \) have free parameters which are chosen to fit QED corrections to the energies (Mohr, et al) and weak matrix elements (Kuchiev, Flambaum; Milstein, Sushkov, Terekhov; Sapirstein et al)
QED corrections to $E_{PV}$ in Cs

$$E_{PV} = \sum_p \frac{W_{sp} E_{1ps}}{E_s - E_p}$$

- QED correction to weak matrix elements leading to $\delta E_{PV}$ (Kuchiev, Flambaum, ’02; Milstein, Sushkov, Terekhov, ’02; Sapirstein, Pachucki, Veitia, Cheng, ’03)
  $$\delta E_{PV} = (0.4-0.8)\% = -0.4\%$$
- QED correction to $\delta E_{PV}$ in effective atomic potential (Shabaev et al, ’05)
  $$\delta E_{PV} = (0.41-0.67)\% = -0.27\%$$
- QED corrections to $E_{1}$ and $\Delta E$ in radiative potential, QED corrections to weak matrix elements are taken from earlier works (Flambaum, Ginges, ’05)
  $$\delta E_{PV} = (0.41-0.73)\% = -0.32\%$$
- QED correction to $\delta E_{PV}$ in radiative potential with full account of many-body effects (Dzuba, Flambaum, Ginges, ’07)
  $$\delta E_{PV} = -0.20\%$$
Overview

• Atoms as probes of fundamental interactions
  • atomic electric dipole moments (EDMs)
  • atomic parity violation (APV)
    - nuclear anapole moment
    - nuclear weak charge
• Nuclear Schiff moment (SM)
• High-precision atomic many-body calculations
• EDMs of diamagnetic atoms
• Strong enhancement of SM in deformed nuclei
• Strong enhancement of EDMs and APV due to close levels of opposite parity
• Summary