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

Victor Flambaum

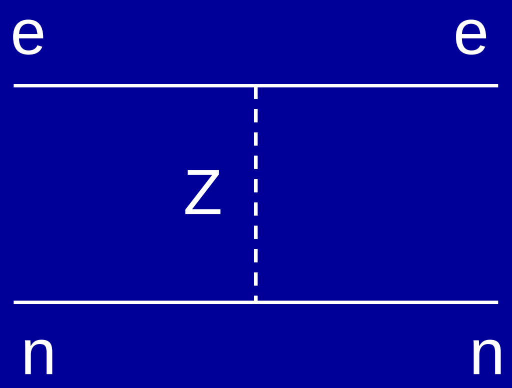
Co-authors: I.Khriplovich, O.Sushkov, V.Dzuba, P.Silvestrov, N.Auerbach, Spevak, J.Ginges, M.Kuchiev, M.Kozlov, A.Brown, A.Derevianko, S.Porsev, J. Berengut, B. Roberts, A. Borschevsky, M.Ilias, K.Beloy, P.Schwerdtfeger

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



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

Standard model tree-level couplings: $C_{1p} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right) \;\; ; \;\; C_{1n} = -\frac{1}{2}$

- 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 $E_{PV} \propto Z^3$ [Bouchiat,Bouchiat]

Discovered in 1978 Bi; Tl, Pb, Cs –accuracy 0.4-1%

Our calculations in 1975-1989 Bi 11%,Pb 8%,Tl 3%,Cs1%

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

$$d_{atom}(1)=2\sum_n\frac{\langle 1|D_z|N\rangle\langle N|H_{PT}|1\rangle}{E_1-E_N}=\xi S$$

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

N_{ve}	Method	Accuracy
0	Rel. Hartree-Fock+RPA	~ 10%
1	RHF+MBPT All-orders sums	0.1-1%
2-8	RHF+MBPT+CI	1-10%
2-15	Configuration interaction	10-20%

N_{ve} *- number of valence electrons*

These methods cover all periodic table of elements

Dzuba,Flambaum,Ginges

$E_{PV} = -0.897(1\pm 0.5\%)\times 10^{-11}\ iea_B(-Q_W/N)$ ➔ $Q_W - Q_W^{SM} = 1.1\ \sigma$

Tightly constrains possible new physics, e.g. mass of extra Z boson $M_{Z'} > 750$ 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} includes -0.8% shift due to strong-field QED self-energy / vertex corrections to weak matrix elements W_{sp}

[Kuchiev,Flambaum; Milstein,Sushkov,Terekhov]

$$E_{PV} = \sum_p \frac{W_{sp} E1_{ps}}{E_s - E_p}$$

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?)

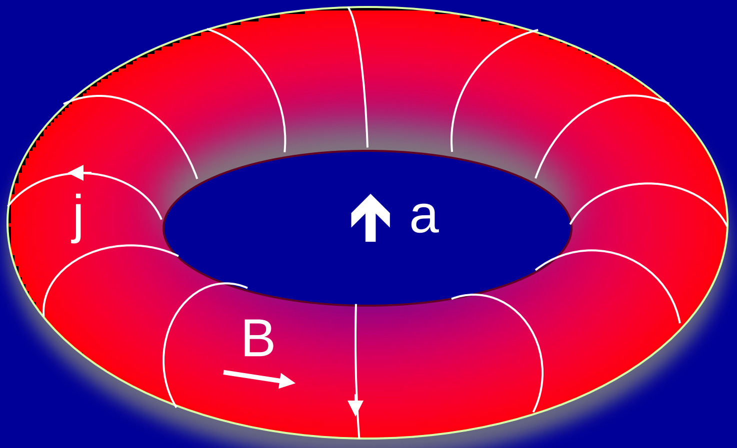
Fortson,Pang,Wilets - neutron distribution problem

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):

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

[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 Λ–doublet.

Ω=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

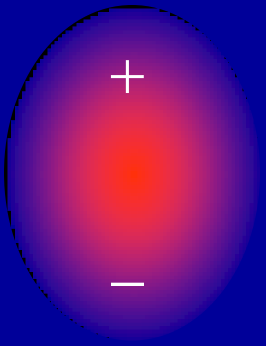
Accurate molecular calculations

- RaF: T.A.Isaev, S. Hoekstra, R.Berger.
- BaF: M.G.Kozlov, A,V.Titov, N.S. Mosyagin, P.V. Souchko. M.N.Nayak,B.Das.

Experimental proposals:

- DeMille et al
- T.A.Isaev, S. Hoekstra, R.Berger.

Atomic electric dipole moments



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

$$\vec{d} \equiv \vec{r} \propto \vec{J}$$

- T-violation ≡ 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!

➔ 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!

e.g. electron EDM

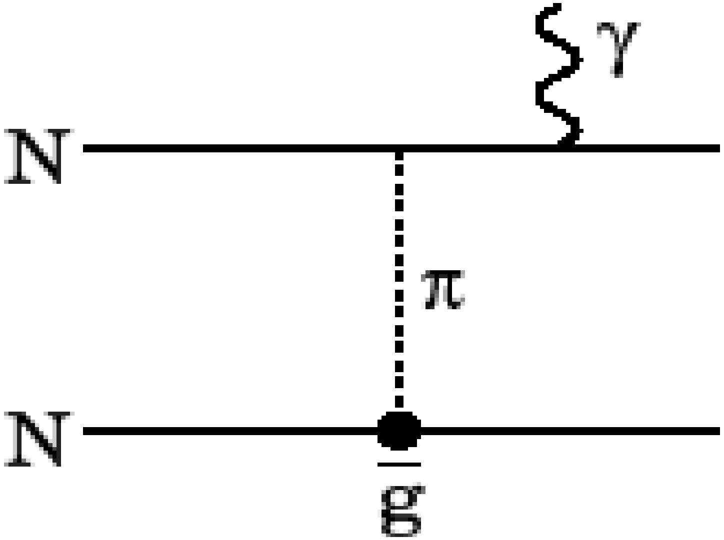
Theory	d_e (e cm)
Std. Mdl.	$< 10^{-38}$
SUSY	$10^{-28} - 10^{-26}$
Multi-Higgs	$10^{-28} - 10^{-26}$
Left-right	$10^{-28} - 10^{-26}$

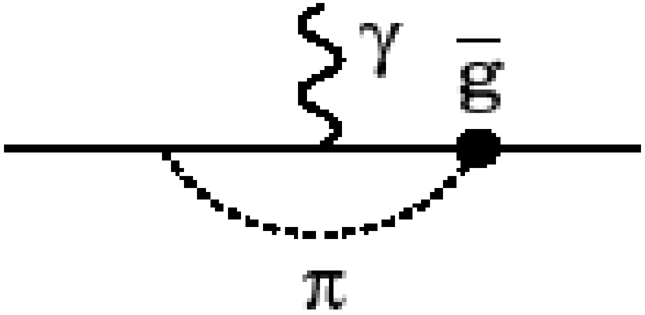
Best limit (90% c.l.): $|d_e| < 1.6 \times 10^{-27}\ e\ cm$ Berkeley (2002)

- Atomic EDMs $d_{atom} \propto Z^3$ [Sandars]

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 π NN and nucleon-nucleon interaction in the Standard model. NN interaction strength 0.3 10^{-8} G. Current limit from atomic EDM 10^{-4} G.
- We need physics beyond Standard model
- Or new enhanced effects.

Atomic EDMs

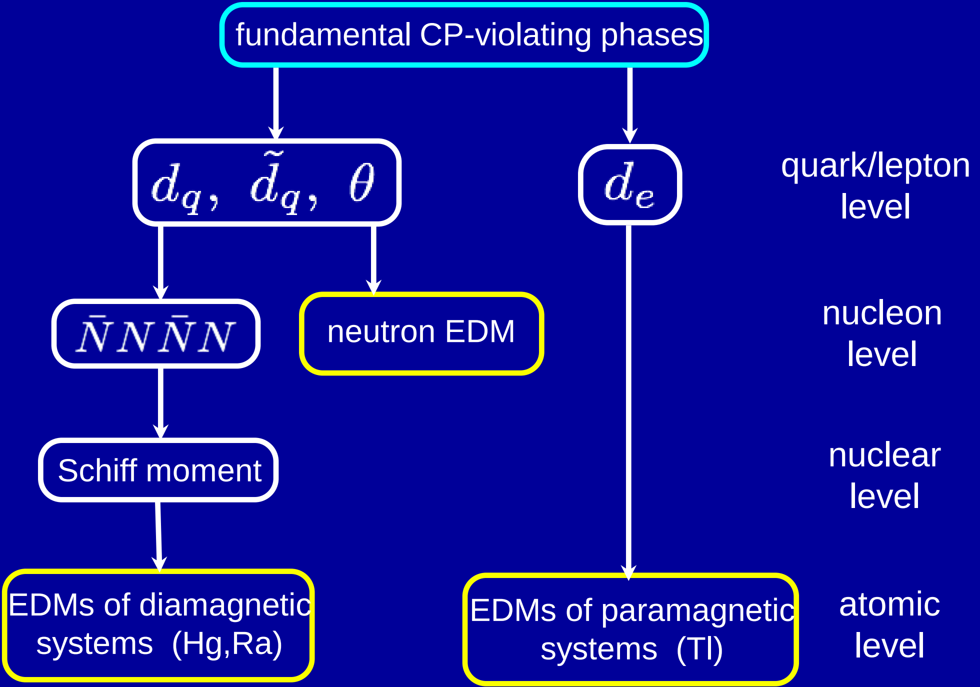
Best limits

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

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

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

Leading mechanisms for EDM generation



fundamental CP-violating phases

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

d_e

quark/lepton level

$\bar{N}N\bar{N}N$

neutron EDM

nucleon level

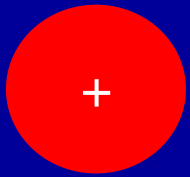
Schiff moment

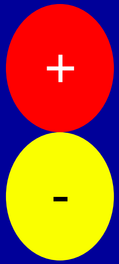
nuclear level

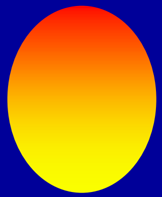
EDMs of diamagnetic systems (Hg,Ra)

EDMs of paramagnetic systems (Tl)

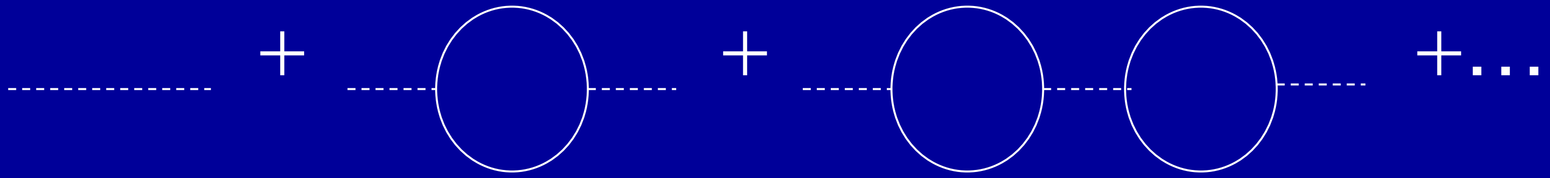
atomic level

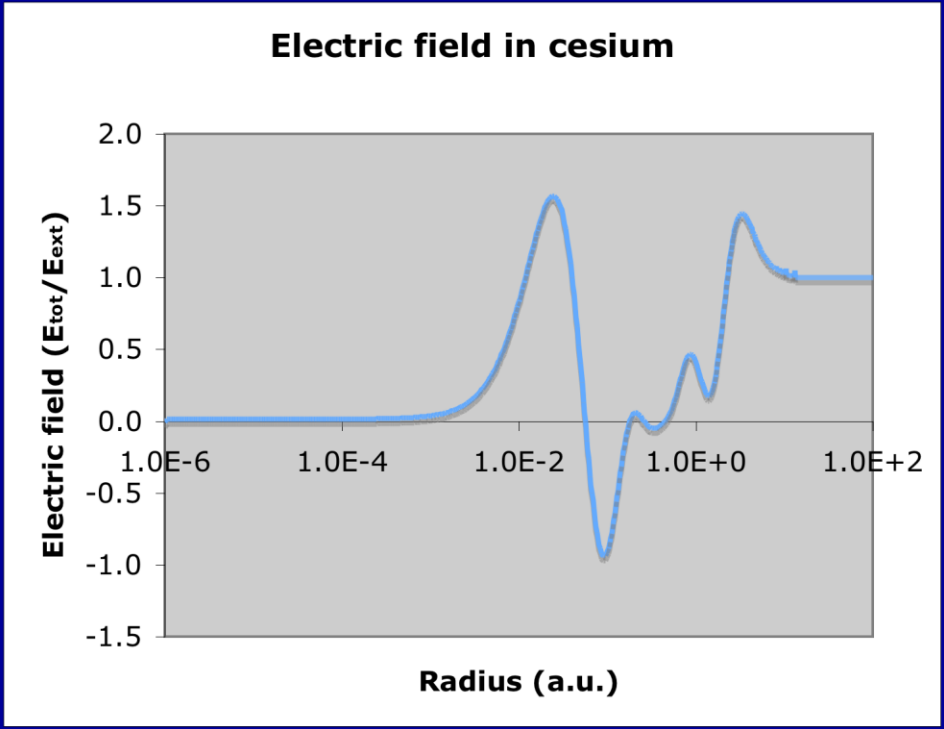
$\psi =$ 

$+\ \beta_{PT}$ 

$|\psi|^2 =$ 

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 $a=Z\, eE_N/M$

$$E_N=E\, Z_i/Z$$

In molecules screening is stronger:

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

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):

$$\varphi(\mathbf{R}) = \int \frac{e\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r + \frac{1}{Z}(\mathbf{d}\bullet\nabla)\int \frac{\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r$$

d is nuclear EDM, the term with **d** is the electron screening term

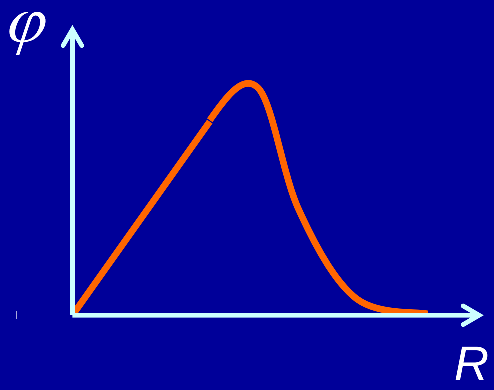
φ(**R**) in multipole expansion is reduced to $\varphi(\mathbf{R}) = 4\pi\mathbf{S}\bullet\nabla\delta(\mathbf{R})$

where $\mathbf{S} = \frac{e}{10}\left[\langle r^2\mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$ is Schiff moment.

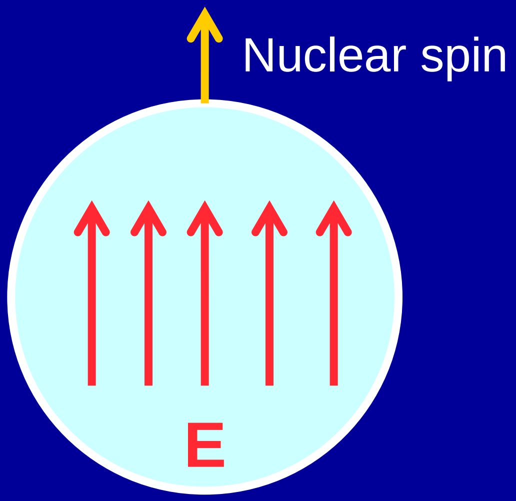
This expression is not suitable for relativistic calculations.

Flambaum,Ginges:
L=S(1 – c Z^2 α^2)

$$\phi(\mathbf{R}) = -\frac{3L \bullet \mathbf{R}}{B}\rho(R)$$ 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.
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, $Z^2 R(Z\alpha)$

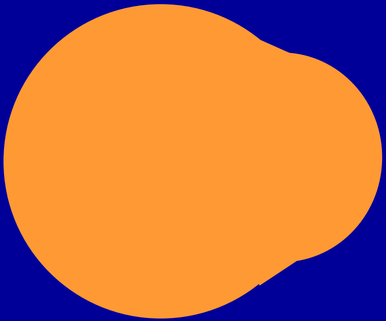
- We perfomed accurate many-body calculations for heavy atoms:Xe,Yb,Hg, Rn,Ra; Measurements for Xe (Seattle,Ann Arbor) and Hg (Seattle).
- In molecules there is an additional enhancement suggested by Sandars: internal electric field of polarised molecule is orders of magnitude larger than applied external field

Calculations and measurements in TlF (Hinds)

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

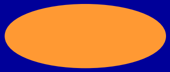
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



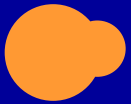
Intrinsic Schiff moment:

$$S_{\mathrm{intr}} \approx eZR_N^3 \frac{9\beta_2\beta_3}{20\pi\sqrt{35}}$$

$\beta_2 \approx 0.2$ - quadrupole deformation



$\beta_3 \approx 0.1$ - octupole deformation

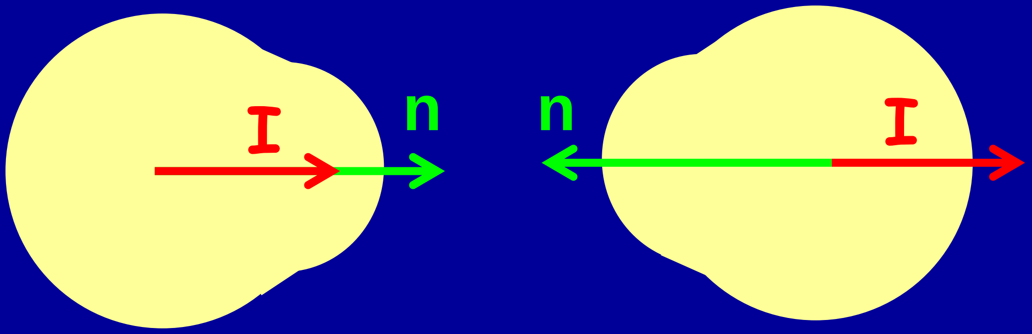


No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame
However, in laboratory frame S=d=0 due to rotation

In the absence of T,P-odd forces: doublet (+) and (-)

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

and $\langle \mathbf{n} \rangle = 0$



$K = (\mathbf{I} \bullet \mathbf{n})$

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

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

and $\langle \mathbf{n} \rangle \propto \beta \mathbf{I}$

EDM and Schiff moment

$$\langle d \rangle, \langle \mathbf{S} \rangle \propto \langle \mathbf{n} \rangle \propto \beta \mathbf{I}$$

Simple estimate (Auerbach, Flambaum, Spevak):

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

Two factors of enhancement:

1. Large collective moment in the body frame
2. Small energy interval (E_+-E_-), 0.05 instead of 8 MeV

$$S \approx 0.05 e \beta_2 \beta_3^2 Z A^{2/3} \eta r_0^3 \frac{\mathrm{eV}}{E_+ - E_-} \approx 700 \times 10^{-8} \eta e \mathrm{fm}^3 \approx 500 S(\mathrm{Hg})$$

^{225}Ra,^{223}Rn, Fr,… -100-1000 times enhancemnt

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}Ra,^{220}Rn,

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	[10^{-25} η] *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
54	^{129}Xe	0.38	0.7	Seattle, Ann Arbor, Princeton
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

Standard Model $\eta = 0.3 \times 10^{-8}$ $d_n = 5 \times 10^{-24}\, e\ \mathrm{cm}\ \eta$, $d(^{199}\mathrm{Hg})/ d_n = 10^{-1}$

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 κ(I n), 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):

$$\mathrm{d}(^{199}\mathrm{Hg}) = -(1.06 \pm 0.49 \pm 0.40) \times 10^{-28}\, e \cdot \mathrm{cm}$$

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

Atomic EDMs

Best limits

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

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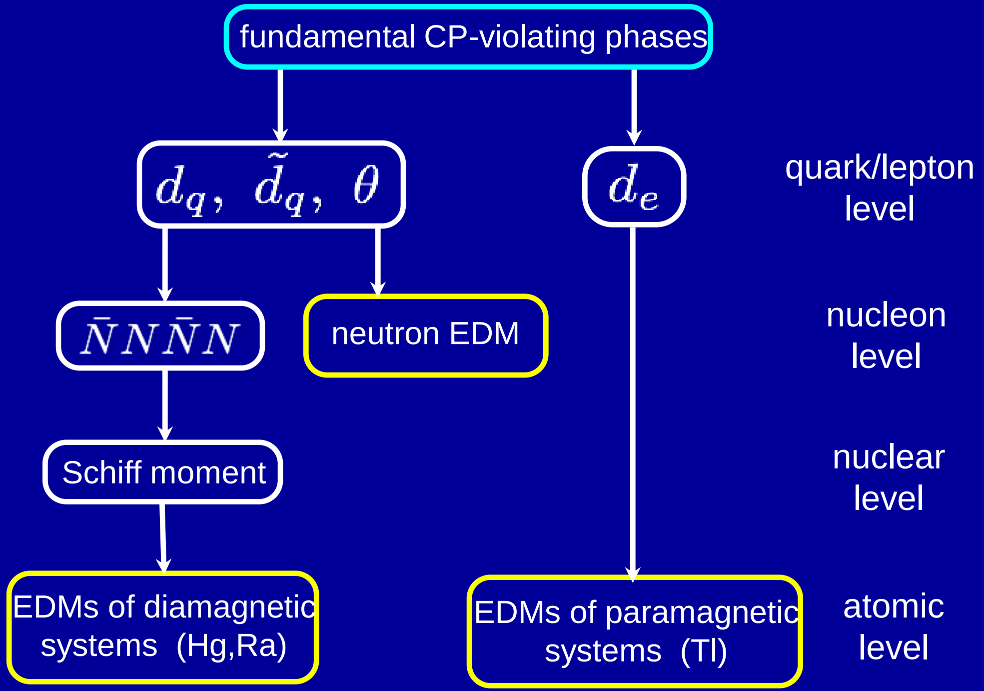
Leading mechanisms for EDM generation


fundamental CP-violating phases

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

d_e

quark/lepton level

$\bar{N}N\bar{N}N$

neutron EDM

nucleon level

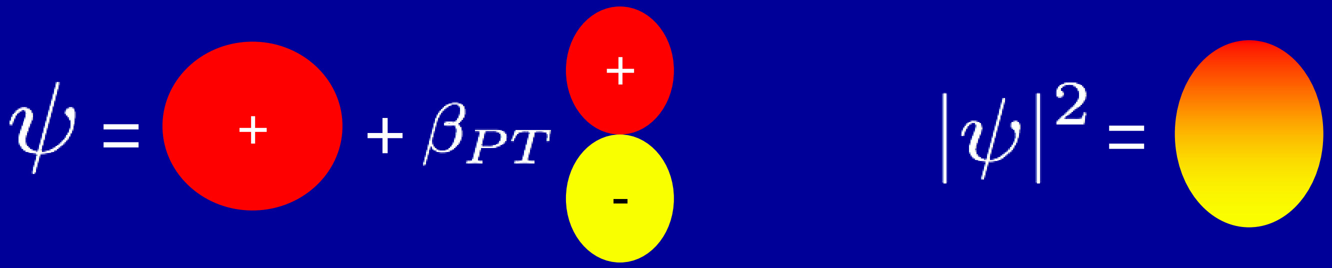
Schiff moment

nuclear level

EDMs of diamagnetic systems (Hg,Ra)

EDMs of paramagnetic systems (Tl)

atomic level



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

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

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels

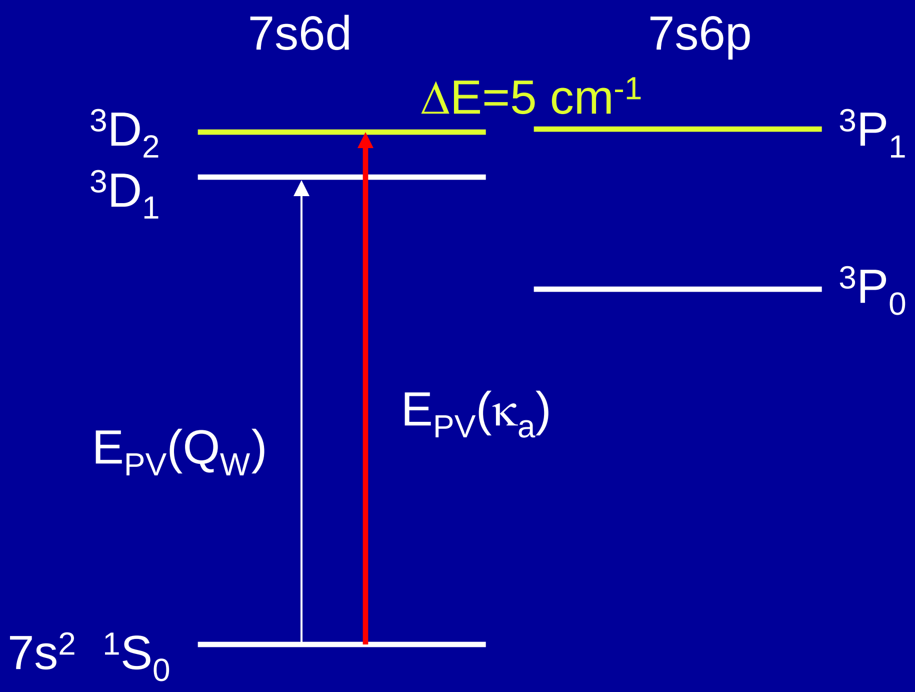
  [Flambaum; Dzuba,Flambaum,Ginges]

$d(^3D_2) \sim 10^5 \times d(Hg)$

Experiment Groningen

$E_{PV}(^1S_0\text{-}^3D_{1,2}) \sim 100 \times E_{PV}(Cs)$

Comparison of even Ra isotopes



Good to study anapole moment:
- Strongly enhanced ($E_{PV} \sim 10^3\, E_{PV}$ (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+

Summary

- 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

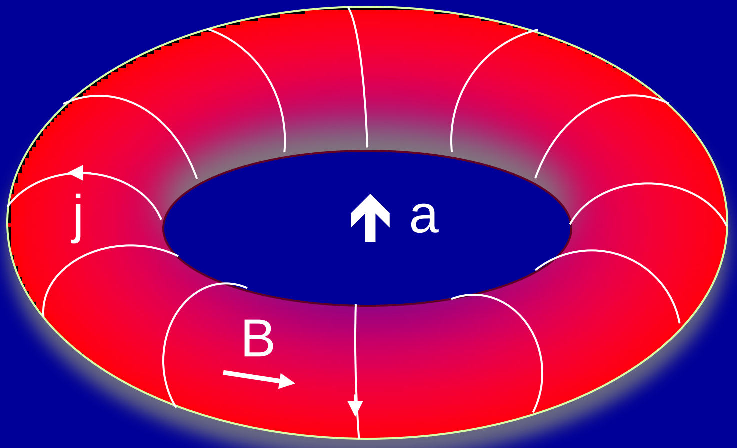
Atoms as probes of fundamental interactions

- 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):

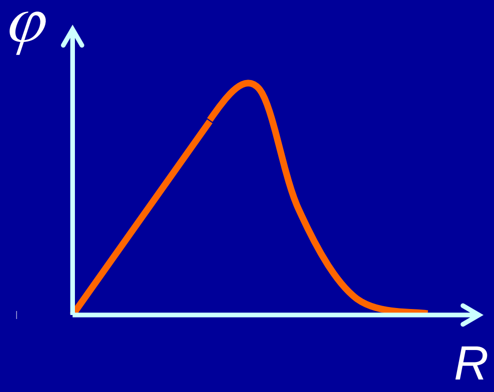
$$h_a = e\vec{\alpha}\cdot\vec{A} \propto \kappa_a \vec{\alpha}\cdot\vec{I}\rho(r)\,, \quad \kappa_a \propto A^{2/3}$$

[Flambaum,Khriplovich,Sushkov]

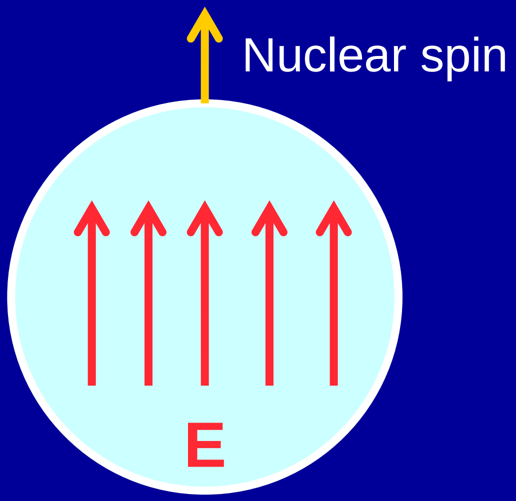
$E_{PV} \propto Z^2 A^{2/3}$ *measured as difference of PV effects for transitions between hyperfine components*

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

Flambaum, Ginges, 2002: $\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R)$ 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**)

$$\mathbf{L} = \sum_{k=1}^{\infty} \mathbf{S}_k$$

$$\varphi(\mathbf{R}) = 4\pi \mathbf{L} \bullet \nabla \delta(\mathbf{R})$$

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 quatrupole moment – not significantly affected

Nuclear electrostatic potential with screening:

$$\varphi(\mathbf{R}) = \int \frac{e\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r + \frac{1}{Z}(\mathbf{d}\bullet\nabla)\int \frac{\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r$$

d is nuclear EDM, the term with **d** is the electron screening term

φ(**R**) in multipole expansion is reduced to $\varphi(\mathbf{R}) = 4\pi\mathbf{S}\bullet\nabla\delta(\mathbf{R})$

where $\mathbf{S} = \frac{e}{10}\left[\langle r^2\mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$ is Schiff moment.

This expression is not suitable for relativistic calculations.

Extra enhancement in excited states: Ra

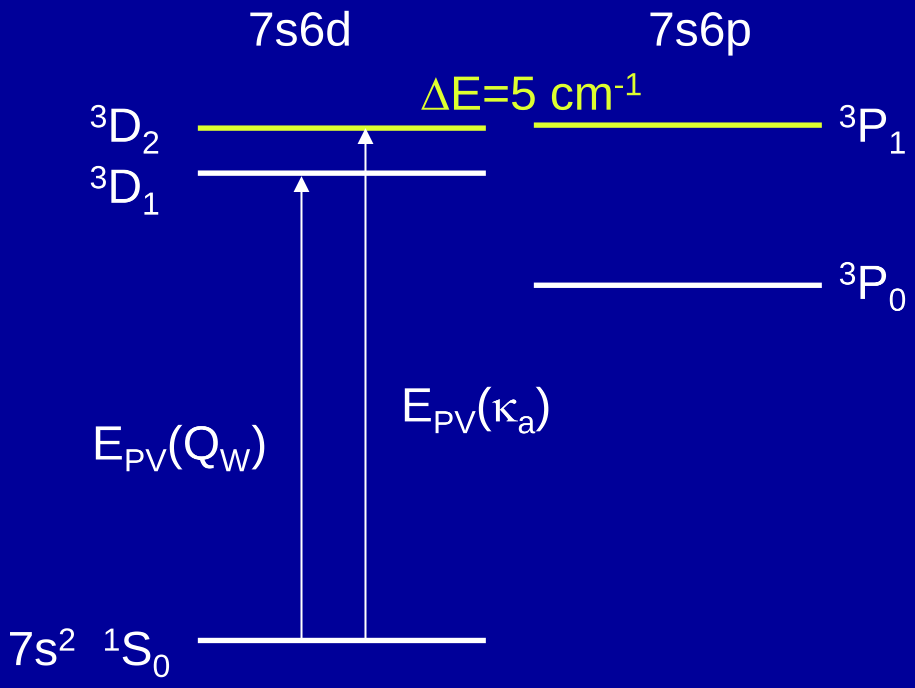
$$d_{atom}(1) = 2\sum_N \frac{\langle 1|D_z|N\rangle\langle N|H_{PT}|1\rangle}{E_1 - E_N}$$

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels

  [Flambaum; Dzuba,Flambaum,Ginges]

$d(^3D_2) \sim 10^5 \times d(\mathrm{Hg})$

$E_{PV}(^1S_0\text{-}^3D_{1,2}) \sim 100 \times E_{PV}(\mathrm{Cs})$



Matrix elements: $<\psi_a|h+\delta V+\delta\Sigma|\psi_b>$

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

h – External field

$<\psi_a|\delta V|\psi_b>$ - Core polarization

$<\psi_a|\delta\Sigma|\psi_b>$ - Structure radiation

Example: PNC *E(6s-7s)* in ^{133} Cs [$10^{-11} iea_B(-Q_W/N)$]

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

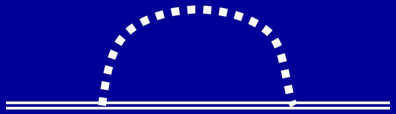
Z	Atom	Even	Odd	ΔE [cm^{-1}]	ΔJ	What
60	Nd II	$^6G_{11/2}$	$^6L_{13/2}$	8	1	S,M
62	SM I	$4f^6 5d6s$	$4f^6 6s6p$	5	0	S,E,M
62	SM I	$^7D_4$	$^9G_5$	10	1	S,M
64	Gd I	$^{11}F_5$	$^9P_3$	0	2	A,M
66	Dy I	$4f^{10} 5d6s$	$4f^{10} 6s6p$	1	1	A,S,M
66	Dy I	$4f^{10} 5d6s$	$4f^9 5d^2 6s$	0	0	A,E,S,M
67	Ho I	$^8K_{21/2}$	$4f^{10} 6s^2 6p$	10	1	S,M

S = Schiff Moment, A = Anapole moment, E = Electron EDM,
M = Magnetic quadrupole moment

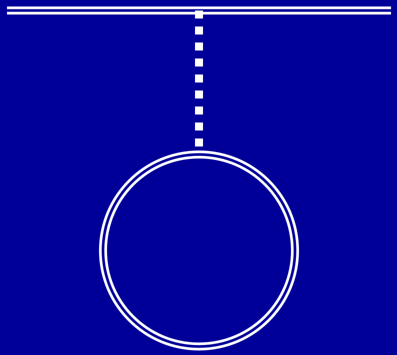
Radiative potential for QED

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

$$\Phi_g(r)+\Phi_f(r)+\Phi_l(r)=$$



$$\Phi_U(r)+\frac{2}{3}\Phi_{WC}^{simple}(r)=$$



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

$\Phi_f(r)$ and $\Phi_f(r)$ 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

$$E_{PV} = \sum_p \frac{W_{sp} E1_{ps}}{E_s - E_p}$$

- QED correction to weak matrix elements leading to δE_{PV} (Kuchiev, Flambaum, '02; Milstein, Sushkov, Terekhov, '02; Sapirstein, Pachucki, Veitia, Cheng, '03)

  δE_{PV} = (0.4-0.8)% = -0.4%

- QED correction to δE_{PV} in effective atomic potential (Shabaev *et al*, '05)

  δE_{PV} = (0.41-0.67)% = -0.27%

- QED corrections to *E1* and ΔE in radiative potential, QED corrections to weak matrix elements are taken from earlier works (Flambaum, Ginges, '05)

  δE_{PV} = (0.41-0.73)%=-0.32%

- QED correction to δE_{PV} in radiative potential with full account of many-body effects (Dzuba, Flambaum, Ginges, '07)

  δE_{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