Violations of parity and time-reversal in atoms and molecules

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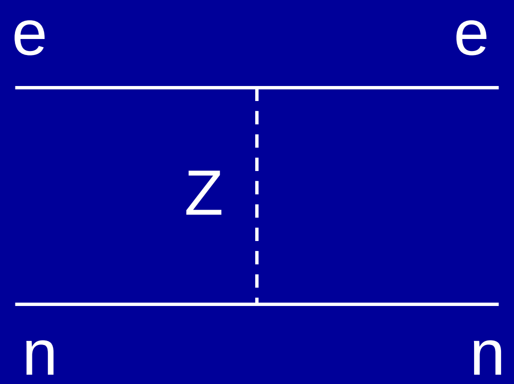
Overview

- Atoms as probes of fundamental interactions
  - *atomic parity violation (APV)*
    - nuclear weak charge
    - nuclear anapole moment
  - *atomic electric dipole moments (EDMs)*
- High-precision atomic many-body calculations
- QED radiative corrections : radiative potential and low –energy theorem for electromagnetic amplitudes
- Cesium APV, test of Standard model
- EDM, test of Time reversal and CP violation theories
- 1000 times enhancement: Radium EDM and APV

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

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

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

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

Clean test of standard model via atomic experiments!
Bi,Pb,Tl,Cs

Recent developments in atomic theory:

Atomic theory	Q_W	$Q_W - Q_W^{SM}$	Ref.
1%-precision MBPT calcs. of Dzuba et al. (1989), Blundell et al. (1990,1992)	$-72.11(27)_{\text{exp}}(89)_{\text{theor}}$	1.2σ	Wood et al. (1997)
Re-interpretation of atomic theory error, $1\% \rightarrow 0.4\%$	$-72.06(26)_{\text{exp}}(34)_{\text{theor}}$	2.5σ	Bennett, Wieman (1999)
+ Breit interaction	$+0.6\%$		Derevianko (2000), Dzuba et al. (2001), Kozlov et al. (2001)
+ Strong-field vacuum polarization	-0.4%		Johnson et al. (2001), Milstein, Sushkov (2002)
+ Neutron skin	$+0.2\%$		Derevianko (2002)
0.5%-precision MBPT calc., incl. all above corrections	$-72.16(29)_{\text{exp}}(36)_{\text{theor}}$	2.1σ	Dzuba et al. (2002)
+ Strong-field QED self-energy and vertex corrections	$+0.8\%$		Kuchiev, Flambaum (2002), Milstein et al. (2002, 2003)

New accurate measurements of E1 amplitudes agree with calculations to 0.1-0.3%
-theoretical accuracy in PV is 0.4% (instead of 1%) Bennet, Wieman 1999
New physics beyond Standard Model !?

New accurate many-body calculations

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

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

E_{PNC} = 0.904(5) (Dzuba, Flambaum, Ginges, 2002)

Calculations in Cs analogues

Ba+

Fr, Ra+ PNC effects 20 times larger

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.

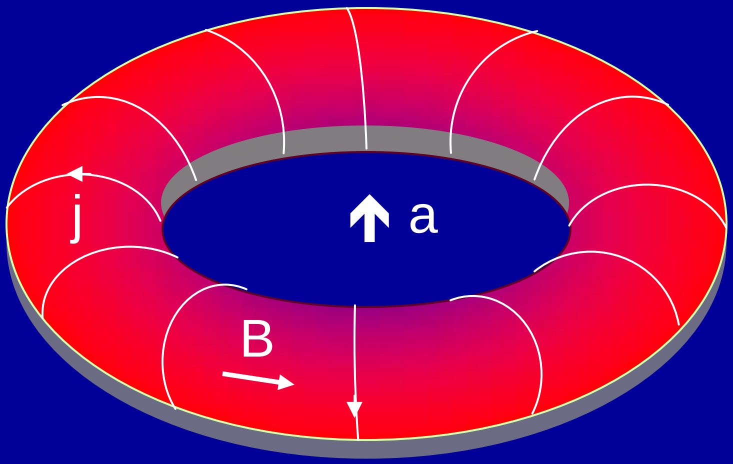
Berkeley: experiments with Dy and Yb

Oxford: Sm   Argonne: Ra   Even Z,N

Test of Standard model or neutron distribution

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 Haxton,Liu,Ramsey-Musolf; Auerbach, Brown; Dmitriev, Khriplovich,Telitsin: problem remains.

Proposals:

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 nuclear anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity. Theorem: only anapole contribution to PV is enhanced (Labzovsky;Sushkov,Flambaum). 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,…

PV effects 10^{-3} , microwave or optical M1 transitions. For example, circular polarization of radiation or difference of absorption of right and left polarised radiation.

Cancellation between hyperfine and rotational intervals-enhancement.

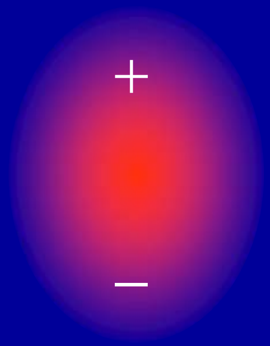
Interval between the opposite parity levels may be reduced to zero by magnetic field – further enhancement.

Many schemes were suggested to study PV for close levels:

Hydrogen 2s-2p, Dy.

Experiment : Yale.

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!

Atomic EDMs

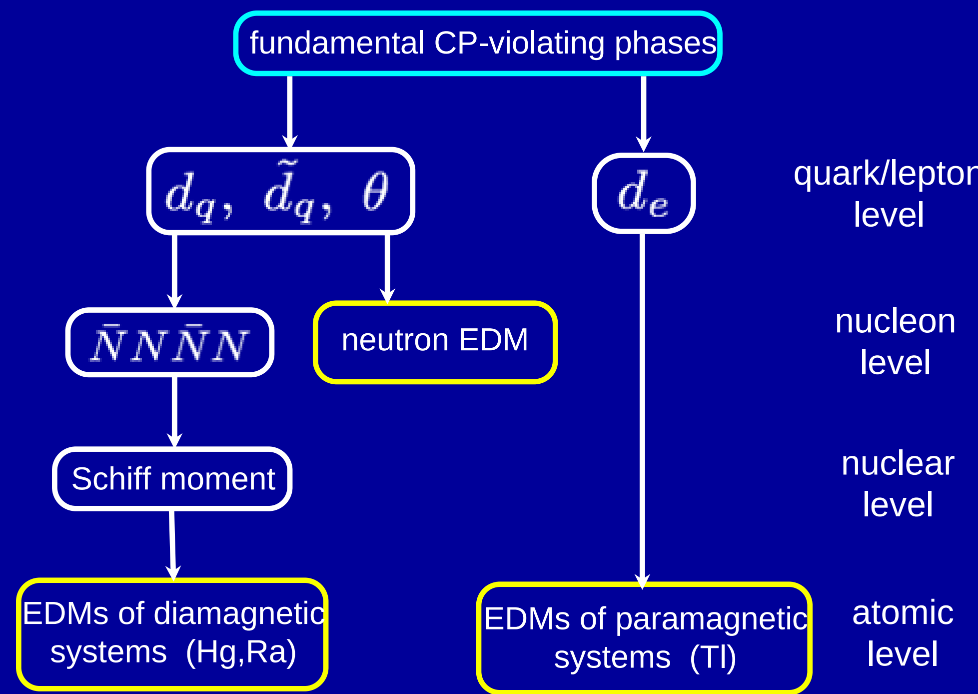
Best limits

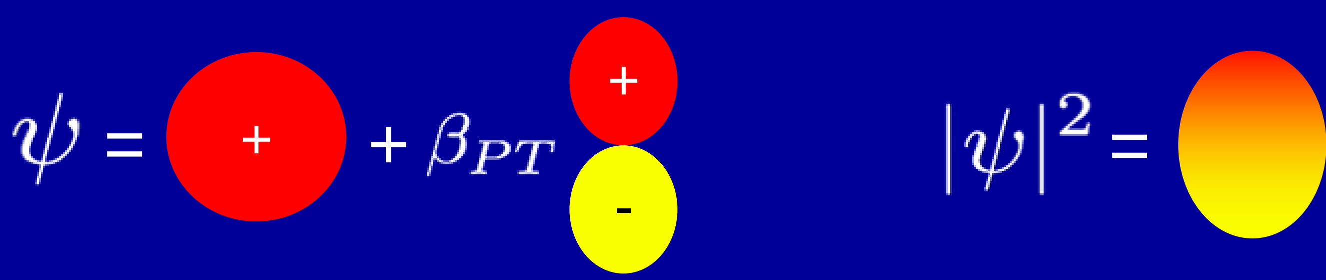
$|d(^{199}\text{Hg})| < 2.1 \times 10^{-28}\ e$ cm
(95% c.l., Seattle, 2001)

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

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

Leading mechanisms for EDM generation





Enhancement of electron EDM

- Atoms: Tl enhancement $d(Tl) = -500\ d_e$
  Experiment – Berkeley
- Molecules –close rotational levels,

Ω –doubling – huge enhancement

$\Omega = 1/2$	10^{7}	YbF	London
$\Omega = 1$	10^{10}	PbO	Yale
$\Omega = 2$	10^{13}	HfF^{+}	Boulder

Weak electric field is enough to polarise the molecule. Molecular electric field is many orders of magnite larger than external field

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:

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

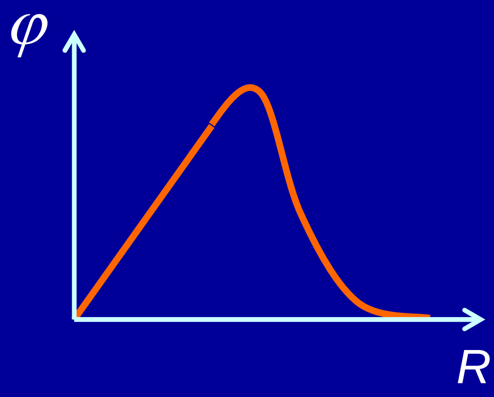
d is nuclear EDM, the term with **d** is the electron screening term

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

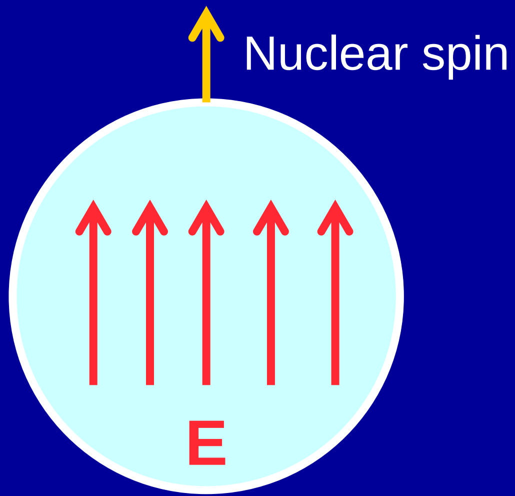
where $\mathbf{S} = \frac{e}{10}\left[\left\langle r^2\mathbf{r}\right\rangle - \frac{5}{3Z}\left\langle r^2\right\rangle\left\langle \mathbf{r}\right\rangle\right]$ is Schiff moment.

This expression is not suitable for relativistic calculations.

Flambaum, Ginges, 2002: $\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R)$ where $B = \int \rho(R) R^4 dR$

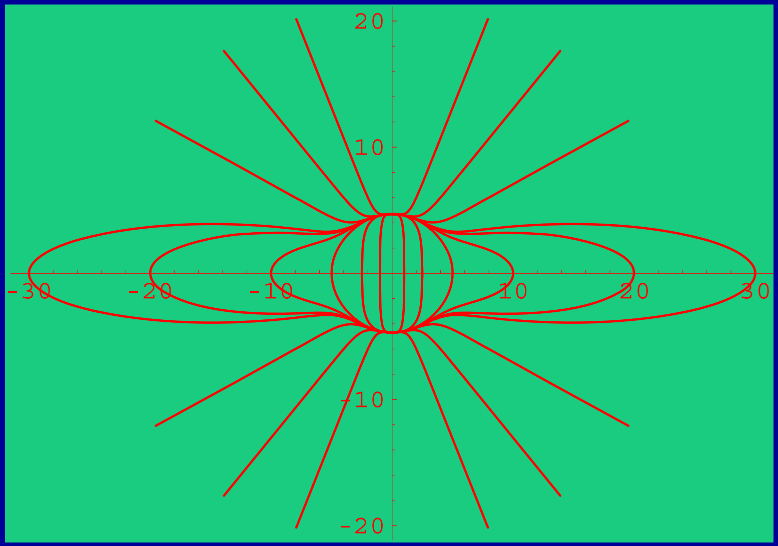


Electric field induced by T,P-odd nuclear forces which influence proton charge density



This potential has no singularities and may be used in relativistic calculations.
SM electric field polarizes atom and produces EDM.
Calculations of nuclear SM: Flambaum,Khriplovich,Sushkov 1984,1986;
Corrections Brown et al,Flambaum et al,Dmitriev et al,Engel et al,Liu et al …
Calculations of atomic EDM: Dzuba, Flambaum,Ginges,Kozlov
Best limits from Hg EDM measurement in Seattle –
Crucial test of modern theories of CP violation (supersymmetry, etc.)

Electric field of Schiff moment (exponentially small outside nucleus, zero at two poles)



Enhancement in nuclei with quadrupole deformation

Close level of opposite parity

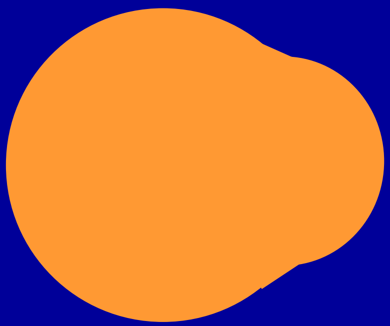
- Haxton, Henley –EDM, MQM
- Sushkov, Flambaum, Khriplovich –Schiff moment
- Flambaum - spin hedgehog and collective magnetic quadrupole are produced by T,P-odd interaction which polarises spins along radius

Enhancement factor does not exceed 10

Nuclear enhancement

(Auerbach, Flambaum, Spevak (1996))

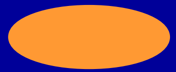
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



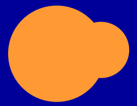
Intrinsic Schiff moment:

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

$\beta_2 \approx 0.2$ - quadrupole deformation



$\beta_3 \approx 0.1$ - octupole deformation



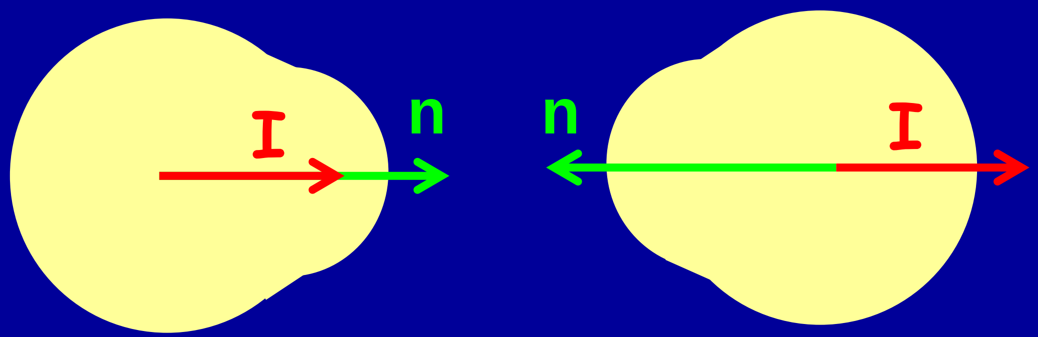
No T,P-odd forces are needed for the Schiff moment in intrinsic reference frame

However, in laboratory frame S=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 $\langle \mathbf{n} \rangle = 0$



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

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

Schiff moment $\langle \mathbf{S} \rangle \propto \langle \mathbf{n} \rangle \propto \beta \mathbf{I}$

Simple estimate (Auerbach, Flambaum, Spevak 1996):

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

Two factors of enhancement:

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

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

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

Atomic calculations

- APV

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

- 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… there are also other checks!

Ab initio methods of atomic calculations

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

N_{ve} - number of valence electrons

These methods cover all periodic table of elements

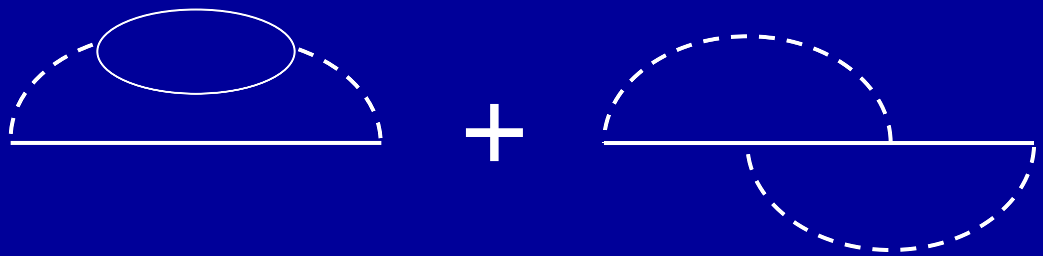
Correlation potential method

[Dzuba,Flambaum,Sushkov (1989)]

- Zeroth-order: relativistic Hartree-Fock. Perturbation theory in difference between exact and Hartree-Fock Hamiltonians.
- Correlation corrections accounted for by inclusion of a “correlation potential” (self-energy operator) Σ (r,r’E):

$$V_{HF} \rightarrow V_{HF} + \Sigma$$

In the lowest order Σ is given by:

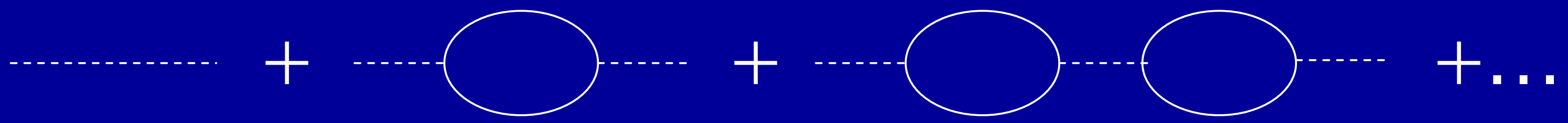
$\Sigma =$ 

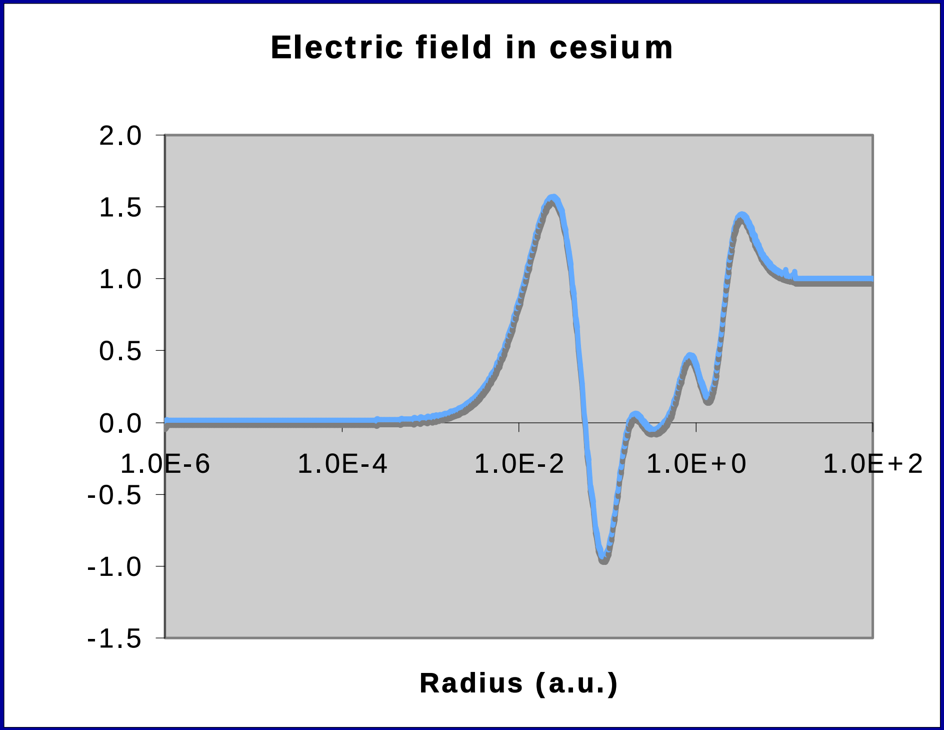
- External fields included using Time-Dependent Hartree-Fock (RPAE core polarization)+correlations

The correlation potential

Use the Feynman diagram technique to include three classes of diagrams to all orders:

1. electron-electron screening





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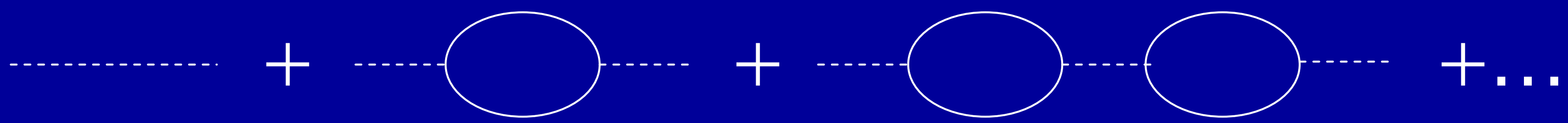
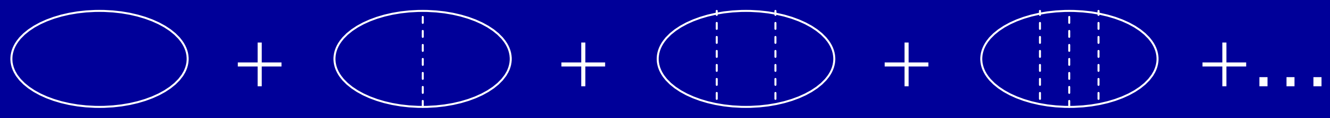
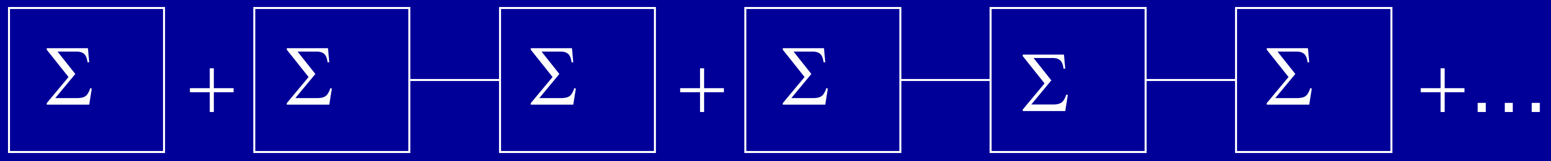


2. hole-particle interaction



3. nonlinear-in-Σ corrections



Best calculation [Dzuba,Flambaum,Ginges, 2002]

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

➔ $Q_W - Q_W^{SM} = 1.1\,\sigma$

Tightly constrains possible new physics, e.g. mass of extra Z boson
$M_{Z'} > 750$ GeV

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

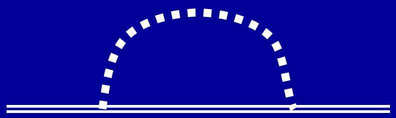
•QED corrections to energy levels and E1 amplitudes

[Flambaum,Ginges; Shabaev,Pachuki,Tupitsyn,Yerokhin]

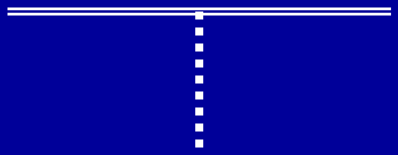
Radiative potential for QED

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

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



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



$\Phi_g(r)$ – 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)

Low-energy theorem to calculate QED radiative corrections to electromagnetic amplitudes

- Small parameter=E/ω

E=energy of valence electron=$10^{-5}\,mc^2$

ω–virtual photon frequency =mc^2

- Results are expressed in terms of self-energy Σ and $d\Sigma/dE$ (vertex, normalization)
- Radiative potential contribution: $\alpha^3 Z^2 \ln(\alpha^2 Z^2)$

Other contributions: $\alpha^3 (Z_i + 1)^2$, Z_i –ion charge

In neutral atoms (Z_i=0) radiative potential contribution is Z^2 times larger!

- Total QED correction to E_{PV}= -0.41%(weak)+0.43%(E1)-0.34%(δE)=-0.32%

Parity violating radiative potential

Flambaum,Shuryak 2007

Z-boson virtual decay to e^+e^-

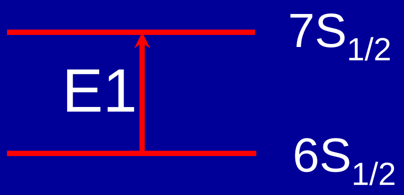
Range is $M_Z/2m_e = 10^5$ times larger than range of usual weak interaction!

(virtual decay to 2 π also increases range of strong interaction due to ρ and σ meson exchange and influences lattice calculation results of meson properties)

PNC in Cs

- Best measurement for cesium [Boulder '97]

$$-\mathrm{Im}(E_{PV})/\beta = 1.5935(1 \pm 0.35\%)\mathrm{mV/cm}$$



- Atomic theory required for determination of Q_W

$$E_{PV}(6s \to 7s) = \sum_n \left[\frac{\langle 7s | H_{PV} | nP \rangle \langle nP | D | 6s \rangle}{E_{7s} - E_{nP}} + \frac{\langle 7s | D | nP \rangle \langle nP | H_{PV} | 6s \rangle}{E_{6s} - E_{nP}} \right] = \zeta Q_W$$

Atomic theory	$\delta E_{PV}/E_{PV}$	Q_W-Q_W^{SM}	Ref.
1% calculations		1.2σ	Dzuba ,Flambaum,Sushkov 1989; Blundell,Johnson,Sapirstein 1990
Reinterpretation 1% to 0.4%		2.5σ	Bennett & Wieman '99
Breit interaction	-0.6%		Derevianko '00
Vacuum polarization	+0.4%		Johnson et al. '01; Milstein & Sushkov '02
Neutron distribution	-0.2%		Derevianko '02
0.5% calculations		2.1σ	Dzuba, Flambaum, Ginges '02
Self-energy and vertex radiative corrections	-0.7%		Kuchiev & Flambaum '02; Milstein et al. '02; Sapirstein et al. '03; Shabaev et al. '05; Flambaum & Ginges '05
Total		1.1σ	

Atoms with several valence electrons: CI+MBPT

[Dzuba, Flambaum, Kozlov (1996)]

CI Hamiltonian: $\Sigma_i h_i + \Sigma_{i<j} e^2/r_{ij}$

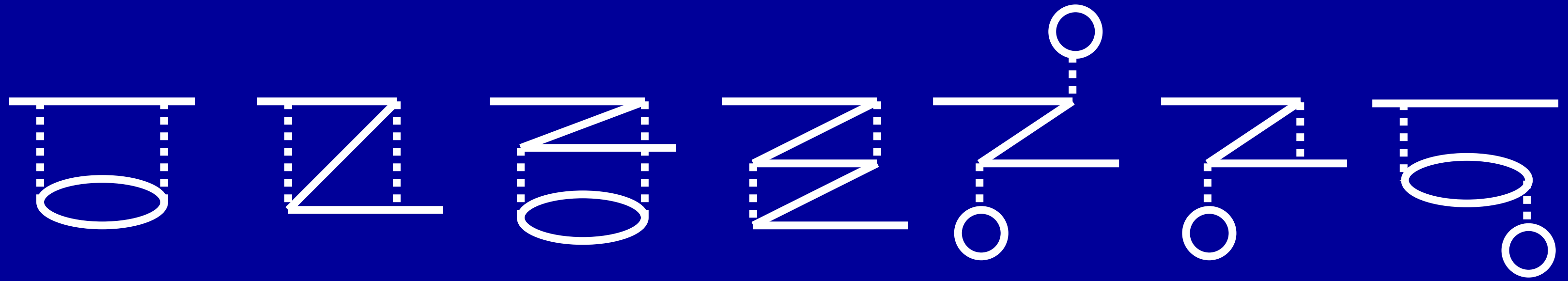
$h = c\alpha\mathbf{p} + (\beta-1)mc^2 - Ze^2/r + V_{core}$

CI+MBPT Hamiltonian:

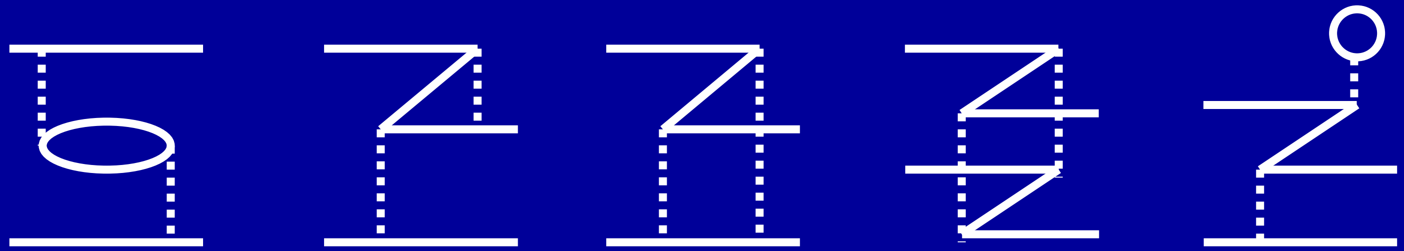
$h \rightarrow h + \Sigma_1$; $e^2/r_{ij} \rightarrow e^2/r_{ij} + \Sigma_2$

MBPT is used to calculate core-valence correlation operator $\Sigma(r,r',E)$

Σ_1:



Σ_2:



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	

$d_n = 5 \times 10^{-24}\, e$ cm η, $d(^{3}\text{He})/ d_n = 10^{-5}$

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, 20001):

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

P,T-odd term	Value	Experiment	
neutron EDM d_n [10^{-26} e cm]	$(17 \pm 8 \pm 6)$ (1.9 ± 5.4) $(2.6 \pm 4.0 \pm 1.6)$	Hg n n	Seattle, 2001 ILL, 1999 PNPI, 1996
proton EDM d_p [10^{-24} e cm]	$(1.7 \pm 0.8 \pm 0.6)$ (17 ± 28)	Hg TlF	Seattle, 2001 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}]	$(1.1 \pm 0.5 \pm 0.4)$ (1.6 ± 4.5) $(2.2 \pm 3.3 \pm 1.3)$	Hg n n	Seattle, 2001 ILL, 1999 PNPI, 1996

Extra enhancement in excited states: Ra

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

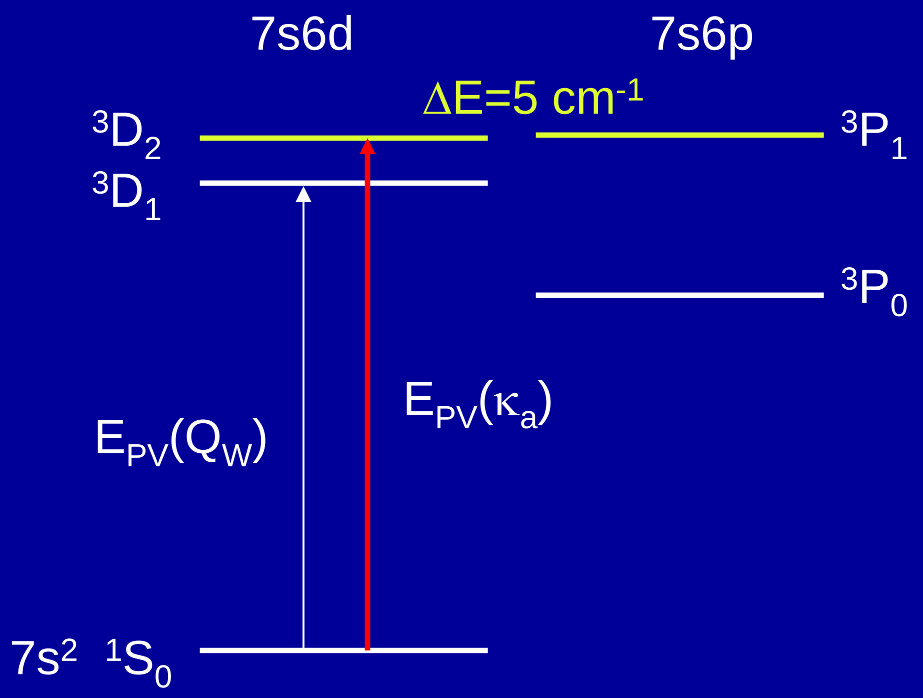
- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels

[Flambaum; Dzuba,Flambaum,Ginges]

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

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

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

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

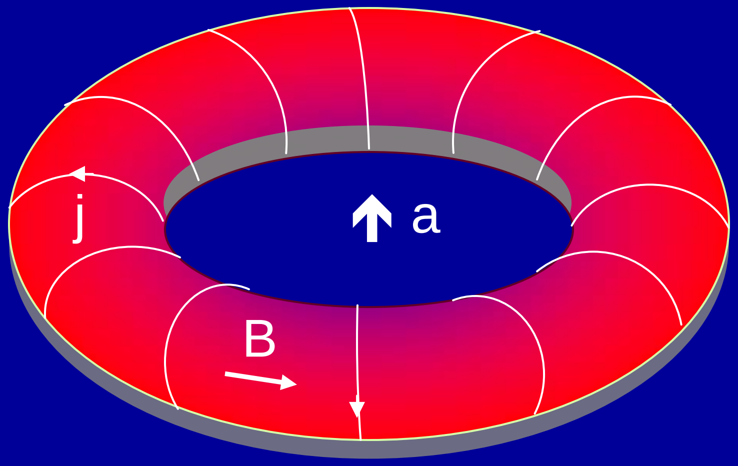
- T,P and P-odd effects in atoms are strongly enhanced:
  - Z^3 or Z^2 electron structure enhancement (universal)
  - Nuclear enhancement (mostly for non-spherical nuclei)
    - Close levels of opposite parity
    - Collective enhancement
    - Octupole deformation
  - Close atomic levels of opposite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

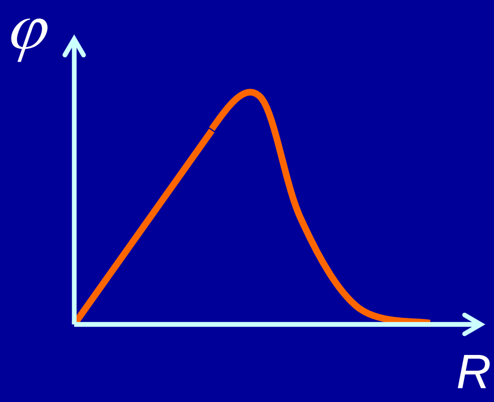
$$h_a = e\vec{\alpha}\cdot\vec{A} \propto \kappa_a \vec{\alpha}\cdot\vec{I}\rho(r)\,, \quad \kappa_a \propto A^{2/3}$$

[Flambaum,Khriplovich,Sushkov]

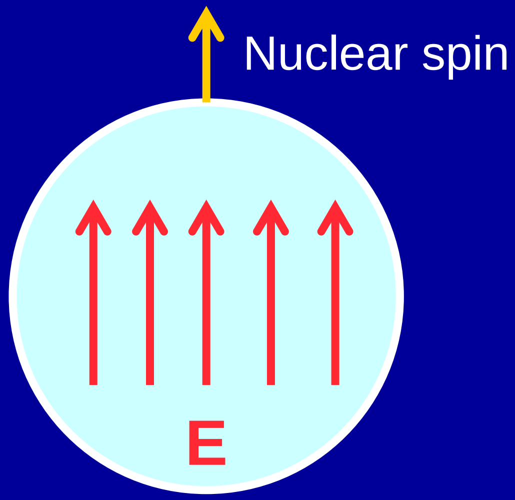
$E_{PV} \propto Z^2 A^{2/3}$ measured as difference of PV effects for transitions between hyperfine components

- 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]

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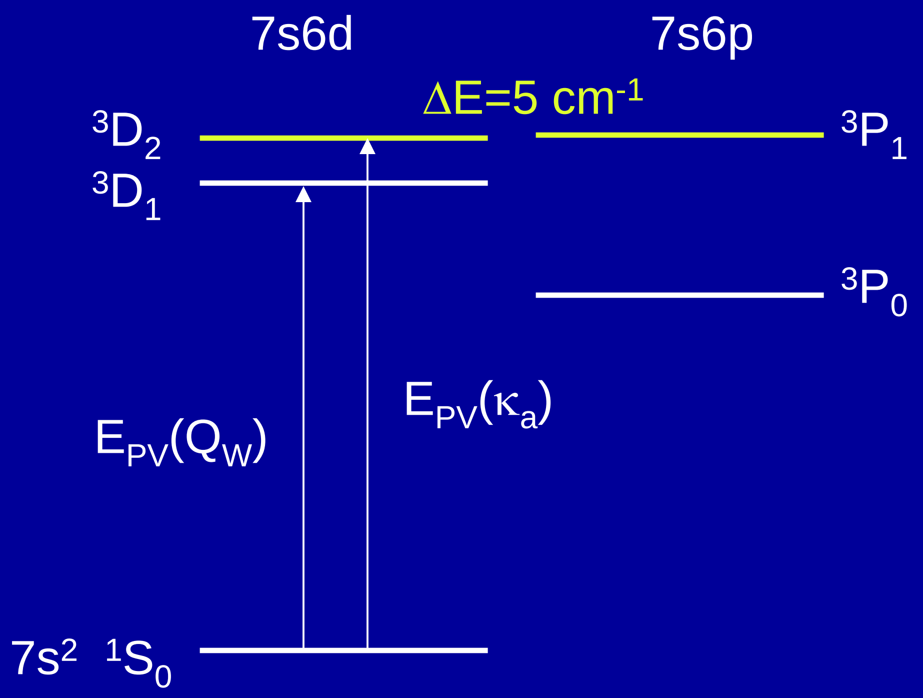


Matrix elements: $<\psi_a|h+\delta V+\delta\Sigma|\psi_b>$

$\psi_{a,b}$ - 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 [$10^{-11} i e a_B(-Q_W/N)$]

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

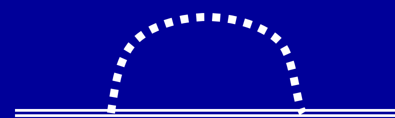
Z	Atom	Even	Odd	ΔE [cm^{-1}]	ΔJ	What
60	Nd II	$^6G_{11/2}$	$^6L_{13/2}$	8	1	S,M
62	SM I	$4f^6 5d6s$	$4f^6 6s6p$	5	0	S,E,M
62	SM I	$^7D_4$	$^9G_5$	10	1	S,M
64	Gd I	$^{11}F_5$	$^9P_3$	0	2	A,M
66	Dy I	$4f^{10} 5d6s$	$4f^{10} 6s6p$	1	1	A,S,M
66	Dy I	$4f^{10} 5d6s$	$4f^9 5d^2 6s$	0	0	A,E,S,M
67	Ho I	$^8K_{21/2}$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

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

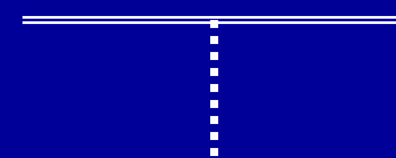
Radiative potential for QED

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

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



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



$\Phi_g(r)$ – 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