Enhanced T-Nonconserving Nuclear Schiff Moment

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- New mechanisms of **CP** violation beyond Standard Model;

Present status of knowledge on EDM

- Neutron

  Expt: $d_n < 6 \cdot 10^{-26}$ e · cm; PRL **82**, 904 (1999);

  SM: $d_n < 10^{-32}$ e · cm

- Electron:

  Expt: $d_e < 1.6 \cdot 10^{-27}$ e · cm; PRL **88**, 071805 (2002);

  SM: $d_e < 10^{-40}$ e · cm

- Muon:

  Expt: $d_\mu < \cdot 10^{-18}$ e · cm; Zs. Phys. G4, 345 (1978);

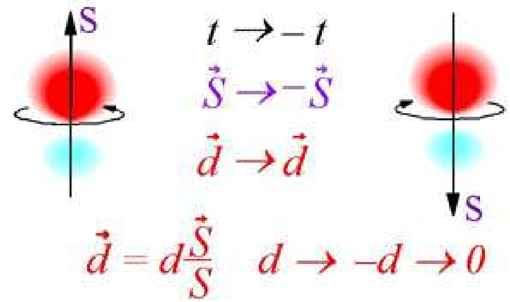
  SM: $d_\mu < 10^{-38}$ e · cm

- Atom:

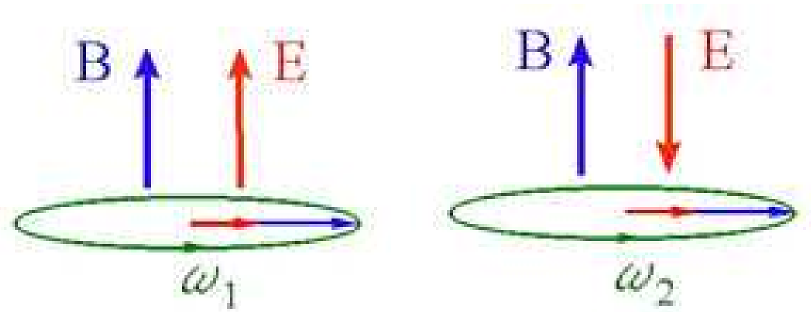
  Expt: d(^{199}Hg) < $2.1 \cdot 10^{-28}$ e · cm; PRL **86**, 2505 (2001);

  $\bar{\theta} < 2 \times 10^{-10}$

Measurements of Atomic EDM



EDM means T- as well as P- nonconseravtion!



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

One measures the Larmor precession frequency of the spins in parallel electric and magnetic fields and alternates the relative orientation of the two fields.

from http://www.phys.washington.edu

Sources of Atomic EDM

- EDM of electron;
- T-reveral violation in lepton-hadron interactions;
- Electromagnetic interaction of electron with P-odd and T-odd moment of nucleus arising from the T-reversal violation component of hadron-hadron interaction;

$$d = 2\sum_k \frac{\langle n|H_{PT}|k\rangle\langle k|D_z|n\rangle}{E_k - E_n}$$

H_{PT} – interaction of electron with nuclear electromagnetic fi eld;

$$H_{PT} = -e\sum_i \varphi(\vec{R}_i)$$

Schiff theorem

For a point nucleus, there exists no term in the interaction with an external field that is linear in electric dipole moment!

For a finite nucleus, the charge and EDM have different spatial distribution:

$\vec{S}$ – Schiff moment

$$\vec{S} = \frac{1}{10} e \sum_{i}^{Z} \vec{r}_i \left(r_i^2 - \frac{5}{3} r_{ch}^2 \right)$$

$$\varphi(\vec{R}) = -3(\vec{S} \cdot \vec{R}) \frac{\rho(R)}{B};$$

$B = \int \rho(R) R^4 dR$; $\rho(R)$ – nuclear density;

Calculations of EDM

$$d = k \cdot 10^{-17} \cdot \left[\frac{\mathbf{S}}{\mathrm{e} \cdot \mathrm{fm}^3} \right] \mathrm{e} \cdot \mathrm{cm}$$

$k = -8.5$ (Ra), $k = 3.3$ (Rn), $k = -2.8$ (Hg), $k = 0.38$ (Xe);
V.A.Dzuba *et al.*, Phys. Rev. A **66**, 012111 (2002);

$$S = 2 \frac{\langle J_0^+ | V_{PT} | J_0^- \rangle \langle J_0^- | \vec{S} | J_0^+ \rangle}{E^+ - E^-}$$

P,T-odd nucleon-nucleon interaction:

$$V_{PT}(1,2) = \frac{G}{\sqrt{2}} \frac{1}{2m_p} \cdot \eta \cdot \left[(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{\nabla}_1 \delta(\vec{r}_1 - \vec{r}_2) \right]$$

Spherical field

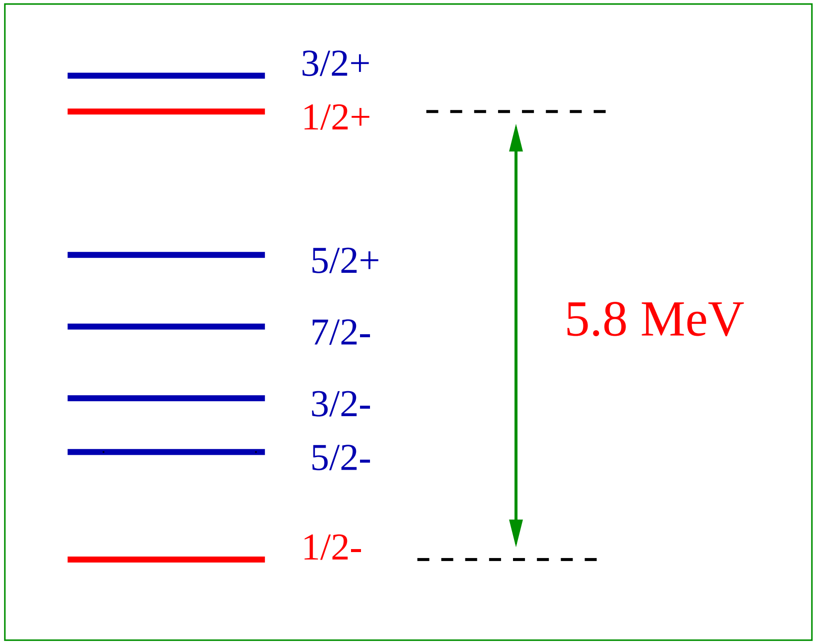
Odd-nucleon in a mean fi eld of spherical core $J = 0^+$ ($A \sim 200$)

$$\Psi(1/2^-) = \Psi(p_{1/2}) + \alpha\Psi(s_{1/2})$$

$$\alpha = \frac{\langle V_{PT}\rangle}{\Delta E} = \frac{0.15\cdot\eta\cdot eV}{5.8\ \mathrm{MeV}}$$

$$\langle s_{1/2}|S_z|p_{1/2}\rangle = 1.0\ \mathrm{e\ fm}^3$$

$$S_{Th}(1/2^-) = 1.0\cdot 10^{-8}\eta e f m^3$$



^{199}Hg case: $\quad\rightarrow\quad d_{\mathrm{Expt}} < 2.1\times 10^{-28} e\cdot cm$

$$|S_{\mathrm{Expt}}| < 7.5\times 10^{-12} e\cdot f m^3; \quad S_{\mathrm{Th}}(1/2^-_{g.s.}) = -1.4\times 10^{-8}\eta\cdot e\cdot f m^3;$$

$$\eta < 0.5\times 10^{-3}$$

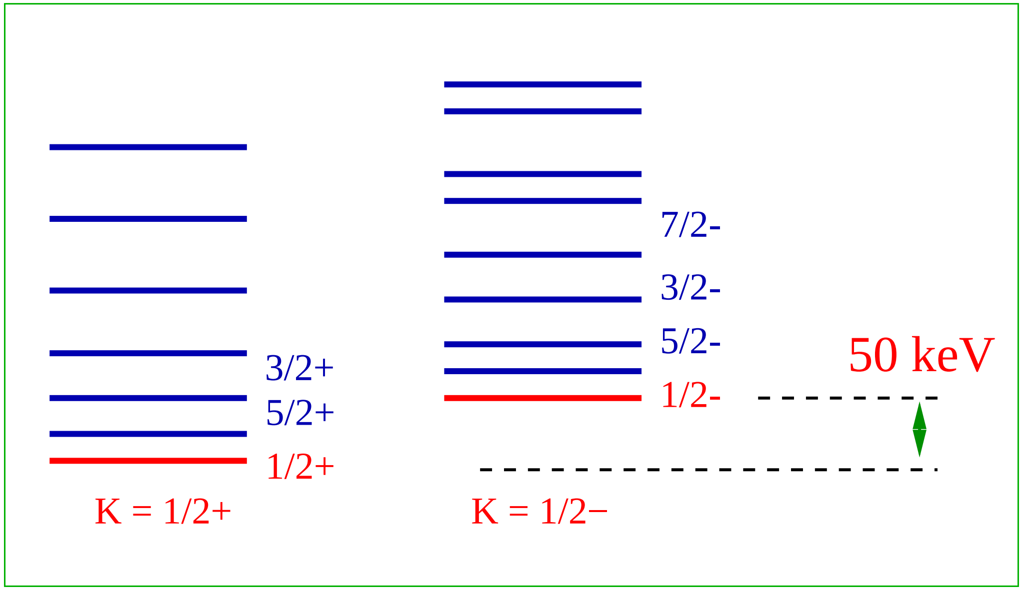
Deformed field

Odd-nucleon in a mean field of deformed rotating core (^{225}Ra)

$$\Psi(1/2^+) = \Psi(K^\pi = 1/2^+) + \alpha\Psi(K^\pi = 1/2^-)$$

$$\alpha = \frac{\langle V_{PT}\rangle}{\Delta E} = \frac{0.15\cdot\eta\cdot eV}{50 \text{ keV}}$$

$$S_{\text{intr}}(K^\pi = 1/2^+) = 20 \text{ e fm}^3$$



$$S_{\text{Th}}(1/2^+) = 0.6\cdot\alpha\cdot S_{\text{intr}} = 300\cdot 10^{-8}\eta e f m^3!!!!$$

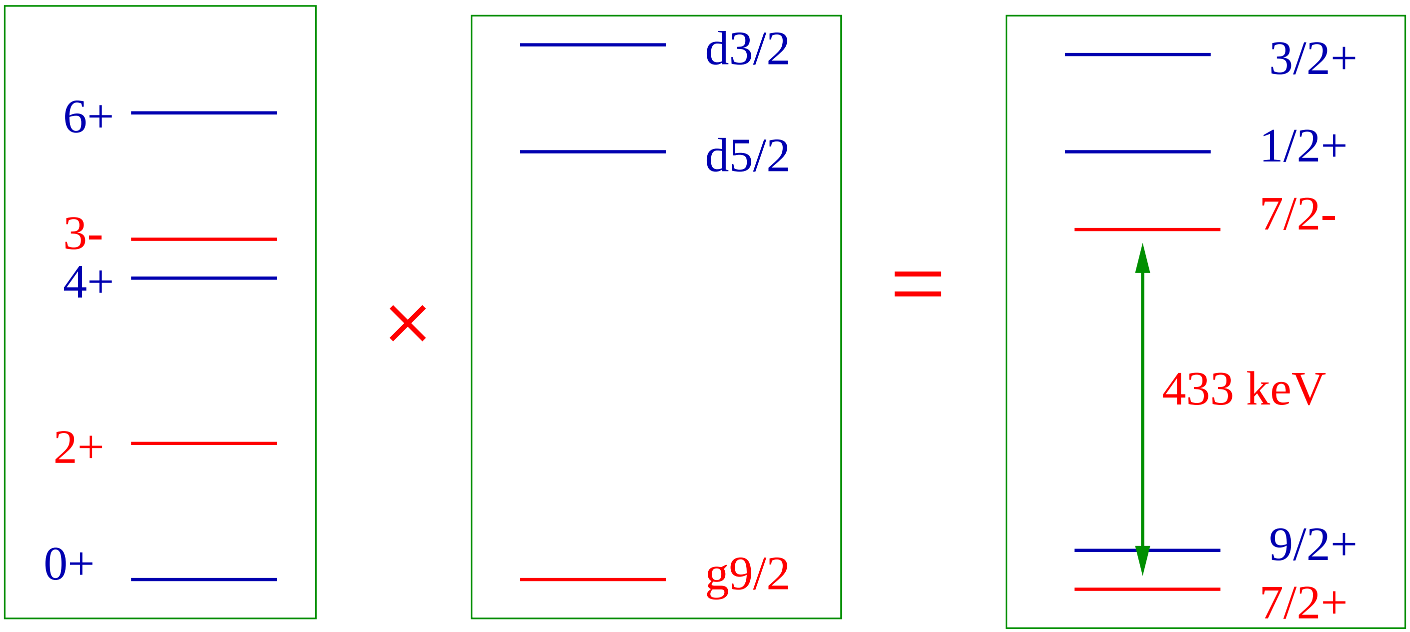
$$S \sim \beta_2\beta_3^2 Z A^{2/3} \qquad\qquad S \sim 10^2 - 10^3 \cdot S(^{199}\text{Hg})$$

[1] N.Auerbach, V.V.Flambaum, V. Spevak, Phys. Rev. Lett. 76, 4316, (1996)

[2] V.V.Flambaum, V.G.Zelevinsky, Phys. Rev. C68, 035502, (2003)

Quadrupole and Octupole vibrations: ^{219}Ra

Quasiparticle-phonon model: Woods-Saxon + pairing (BCS) + collective quadrupole-quadrupole and octupole-octupole forces (QRPA): **A. F. Lisetskiy, V.V.Flambaum, V.G.Zelevinsky, in preparation**



$$\Psi(7/2^+) = \Psi([g_{9/2} \otimes 2^+]^{7/2+}) + \alpha \Psi([g_{9/2} \otimes 3^-]^{7/2-})$$

$$\alpha = \frac{\langle V_{PT} \rangle}{\Delta E} = \frac{0.08 \cdot \eta \cdot eV}{433 \text{ eV}} \qquad \langle 7/2^+ | S_z | 7/2^- \rangle = 2.0 \text{ e fm}^3$$

$$S_{Th}(7/2^-) = 70.0 \cdot 10^{-8} \eta e f m^3$$

Results

Schiff moment **S** $[\eta \cdot 10^{-8} e fm^3]$ and
Atomic dipole moment d $[\eta \cdot 10^{-25} e fm^3]$

Nucleus	Structure g.s. (J^+)	J^-	ΔE^{th} [keV]	S^{th}	d^{th}_{at}
$^{217}_{88}$**Ra**$_{129}$	$\frac{9}{2}^+[g_{\frac{9}{2}} \times 0^+]$	$\frac{9}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**1384**	**1.58**	**13.4**
$^{217}_{86}$**Rn**$_{131}$	$\frac{9}{2}^+[g_{\frac{9}{2}} \times 0^+]$	$\frac{9}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**1296**	**3.31**	**10.9**
$^{219}_{88}$**Ra**$_{131}$	$\frac{7}{2}^+[g_{\frac{9}{2}} \times 2^+]$	$\frac{7}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**434**	**70.1**	**596**
$^{219}_{86}$**Rn**$_{133}$	$\frac{5}{2}^+[g_{\frac{9}{2}} \times 2^+]$	$\frac{5}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**969**	**18.5**	**61.1**
$^{221}_{88}$**Ra**$_{133}$	$\frac{5}{2}^+[g_{\frac{9}{2}} \times 2^+]$	$\frac{5}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**991**	**51.7**	**440**
$^{221}_{86}$**Rn**$_{135}$	$\frac{7}{2}^+[g_{\frac{9}{2}} \times 2^+]$	$\frac{7}{2}^-[g_{\frac{9}{2}} \times 3^-]$	**567**	**15.6**	**51.5**
$^{211}_{86}$**Rn**$_{125}$	$\frac{1}{2}^-[p_{\frac{1}{2}} \times 0^+]$	$\frac{1}{2}^+[f_{\frac{5}{2}} \times 3^-]$	**2222**	**0.23**	**0.8**

Conclusion

- Considerable enhancement of Schiff moments in atomic nuclei with soft quadrupole and octupole vibrations is possible: $10 - 100 \cdot S(^{199}Hg)$
- Nuclear structure enhancement sources:
  - large amplitude of the $[j^{\pm} \times 2^{+}_{\mathrm{vib}}]; J^{\pm}$ component in $J^{\pm}$ g.s. and large amplitude of the $[j^{\pm} \times 3^{-}_{\mathrm{vib}}]; J^{\mp}$ component in excited $J^{\mp}$ state
  - closeness of 2^{+} and 3^{-} phonons
  - PT-nonconserving nucleon-nucleon interaction is not enhanced
- Improvements and extensions of the models: quasiparticle-plus-two-phonon contribution ($[2^{+} \times 3^{-}]$, $[2^{+} \times 2^{+}]$), "mixed-symmetry" proton-neutron 2^{+} phonons, core polarization, realistic nucleon-nucleon interactions,...
- Systematic of calculated Schiff moments in different mass regions
- Correlation of Schiff moment with B(E2), B(E1) and B(E3) strength
- New EDM experiments are planned at ANL (^{225}Ra), TRIUMF (^{211}Rn), KVI, University of Washington, SUNY,... $\rightarrow$ nuclear theory input is urgently required!