- **Low energy tests of the standard model**
  - Cs atom
  - Tl atom
  - Fr, Ba^+, Yb and Dy atoms
  - Role of the Breit interaction
- **Measurements of the anapole moments of the nuclei**
  - Anapole moment of ^{133}Cs
  - Project of the RF experiment on ^{41}K
- **Search for the EDM of the electron**
  - YbF molecule
  - PbO molecule

Weak charge and test of standard model

Experiment on $6s \longrightarrow 7s$ transition in Cs.

The most accurate measurement was done in Boulder in 1997:

$$\frac{\mathrm{Im}E1_{\mathrm{PNC}}}{\beta} = -1.5939(56)\frac{\mathrm{mV}}{\mathrm{cm}},$$

where β is the Stark-induced amplitude, which was recently remeasured:

$$\beta = 27.024(43)(67)\mathrm{a.u.}$$

The most accurate calculations were done in Novosibirsk (1989) and Notre Dame (1990):

$$\mathrm{Im}E1_{\mathrm{PNC}} = -10^{-11}\left(\frac{Q_W}{N}\right)\begin{cases} 0.908(10) & \text{Novosibirsk;} \\ 0.905(9) & \text{Notre Dame.} \end{cases}$$

Later these results were used to obtain the following experimental values of the weak charge of ^{133}Cs:

$$Q_W = \begin{cases} -72.41(25)(80) & \text{Dzuba, Flambaum, and Sushkov;} \\ -72.06(28)(34) & \text{Bennett and Weiman;} \\ -72.42(28)(34) & \text{Derevianko.} \end{cases}$$

These values should be compared with the standard model prediction

$$Q_W = -73.20(13).$$

Note. The main difference between theoretical results come from Breit correction. Novosibirsk group ignored Breit correction, Notre Dame group gave the value -0.2%, and Derevianko gave -0.6% value.

Experimental and theoretical values of $R = \frac{\mathrm{Im} E1_{\mathrm{PNC}}}{M1}$ for $6p_{1/2} \longrightarrow 6p_{3/2}$ transition in ^{205}Tl

Experiment

Oxford	Edwards *et al* (1995)	-15.68 (0.45)
	Majumder and Tsai (1999)[1]	-14.71 (0.45)
Seattle	Vetter *et al* (1995)	-14.68 (0.17)

Theory

(Standard model value $Q_W = -116.8$ assumed)

Novosibirsk	Dzuba *et al* (1987)	-15.1 (0.5)
Notre Dame	Liu *et al* (1996)[2]	-16.1 (1.0)
Gatchina	Kozlov *et al* (1997)	-15.0 (0.6)
Gatchina	Kozlov and Porsev (2000)	-15.6 (0.5)

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[1] scaling of Oxford result

[2] unpublished

Anapole moment of the nucleus

Experiment on $6s \longrightarrow 7s$ transition in Cs.

The first measurement of the nuclear-spin-dependent (NSD) PNC amplitude was done in Boulder in 1997:

$$\frac{\mathrm{Im}E1_{\mathrm{PNC}}}{\beta} = \begin{cases} -1.6349(80)\ \mathrm{mV/cm},\ F=4 \rightarrow F'=3, \\ -1.5576(77)\ \mathrm{mV/cm},\ F=3 \rightarrow F'=4. \end{cases}$$

These values give the following constant of the NSD weak interaction:

$$\kappa = 0.442(62).$$

There are three contributions to this constant (Flambaum and Khriplovich):

$$\kappa = (-1)^{I+1/2+l}\kappa_a + \kappa_2 + \kappa_Q,$$

where κ_a is the anapole moment of the nucleus, κ_2 is the constant of the $A_N \times V_e$ weak interaction and κ_Q arise from the interference of the $V_N \times A_e$ weak interaction with the hyperfine interaction. Assuming the SM values for the two latter terms, one can extract the anapole moment and compare it with nuclear theory prediction based on the "best values" for the constants of the weak meson-nucleon interaction:

$$\begin{array}{lll} \kappa_a & = 0.364(62) & \text{(Flambaum and Murray)}, \\ \kappa_a^{\mathrm{BV}} & = 0.27 & \text{(Dmitriev and Telitsin)}. \end{array}$$

Using the experimental value of the anapole moment Flambaum and Murray derived the constant of the weak nuclear potential

$$g_p = 7.3 \pm 1.2 \pm 1.5.$$

Experiment on the hyperfine transition of the ground state of ^{41}K.

(Under preparation by Petersburg-Brighton-Bonn collaboration).

- The PNC part of the transition amplitude depends on the RF magnetic and electric fields $\vec{\beta}_1$ and $\vec{\varepsilon}_2$ and the static magnetic field $\vec{B}_0$:

$$S_{\mathrm{PNC}} \propto (\vec{\beta}_1 \times \vec{B}_0 \cdot \vec{\varepsilon}_2)\kappa.$$

- PNC effect is completely determined by the NSD amplitude. *No contribution from the weak charge!*
- Relatively light atom, therefore the theory of the weak nuclear forces can be tested for a different (and simpler) case than in experiment with Cs.
- Line width for the hyperfine transition can be made $1 \div 10$ Hz. That gives very high statistical sensitivity if optical pumping and detection are used ($1\% \Longleftrightarrow 20$ min).
- The low frequency (about 60 MHz) allows to conrol amplitudes and phases of RF fields.
- Main spurious effect is proportional to $1/B_0$, while the transition frequency and PNC effect only weakly depend on B_0.

EDM of the electron in diatomic radicals

Comparison with atoms

♡ Large enhancement factors

♡ Relative simplicity of the theory, reliable calculations of enhancement factors

♠ Chemically unstable, available only in a beam

♠ Small intensity and dense spectrum, therefore low statistics

♠ High sensitivity to stray fields

Choice of the molecule

- *Theoretical requirements.* (i) Large Z, (ii) Ground state $^2\Sigma_{1/2}$, (iii) Polar molecule, (iv) Simple electronic structure.
- *Experimental requirements.* (i) Possibility to produce intense beam, (ii) Possibility to use optical pumping and detection.

→ *Molecule with largest enhancement:* **HgF**

⇒ *Compromise molecule:* **YbF** (Hinds)

Experiments on YbF

- 1995: Preliminary measurement of the EDM of the electron on YbF (Sauer, Wang, and Hinds)
- New measurement underway in Sussex (Sauer and Hinds)

Calculations of EDM enhancement factor for YbF

Calculations of hyperfine constants and matrix elements of H_d (W_d), H_2^P (W_A), and $H_S^{P,T}$ (W_S) for ^{171}YbF. Notations: SE- semiempirical method, GRECP - Generalized relativistic effective core potential method, RAS - restricted active space method, (U)DHF - (Unrestricted) Dirac-Hartree-Fock method, EO - effective operator method.

		A (MHz)	A_d (MHz)	W_d $(10^{25}\frac{\text{Hz}}{\text{e cm}})$	W_A (Hz)	W_S (kHz)
Experiment	[1]	7617	102			
SE	[2]	”	”	-1.26		-43
DHF	[3]	7865	60	-0.60	310	-21
UDHF	[4]			-1.20		-22
GRECP+RAS+EO	[5]	7839	94	-1.21	634	

1. van Zee *et al* 1978
2. Kozlov 1997
3. Quiney *et al* 1997
4. Parpia 1998
5. Mosyagin *et al* 1998

EDM of the electron in PbO molecule

History

- 1979: Flambaum and Sushkov suggested to look for the Faraday effect in the electric field in $X_0 - a_1$ optical transition of PbO molecule.
- 1988: Barkov, Zolotorev and Melik-Pashaev (Budker) noted that nonlenear Faraday effect give several orders enhancement.
- 1998: DeMille suggested to use long lifetime of a_1 level to pump it and look for the presession of spin in electric field
- 2000: DeMille and Hunter started preliminary experiments and measured:
  - lifetimes of several levels including a_1
  - isotope shift (IS) between ^{208}Pb and ^{206}Pb isotopes for $X_0 - a_1$ transition
  - hyperfine structure (HFS) constant for a_1 level

Comparison with other experiments

♡ Stable and easily produced molecule

♡ Probably (!) large enhancement factor

♡ Possibility to work in a cell rather than a beam

♡ 100% polarization in electric field 10 V/cm

♠ Difficult to pump and probe

♠ Difficult to calculate enhancement factor (excited state with two unpaired electrons)

Semiempirical estimate of EDM enhancement in PbO

Assume the following structure of the three lower levels of PbO:

$$\begin{aligned} |X,0\rangle &= |\sigma_{1/2},\sigma_{-1/2}\rangle, && (1)\\ |a,1\rangle &= |\sigma_{1/2},\sigma'_{1/2}\rangle, && (2)\\ |b,0\rangle &= |\sigma_{1/2},\sigma'_{-1/2}\rangle, \end{aligned}$$

where one electron orbitals σ and σ' can be expanded in atomic basis:

$$\begin{aligned} |\sigma\rangle &= C_s|6s\rangle + C_p|6p_z\rangle + \text{orbitals centered on oxigen}, && (3)\\ |\sigma'\rangle &= C'_s|6s\rangle + C'_p|6p_z\rangle + \quad \text{''} \qquad \text{''} \qquad \text{''} \quad . && (4) \end{aligned}$$

In this model the EDM enhancement is determined by the constant W_d:

$$\begin{aligned} &\langle a_1|H_{edm}|a_1\rangle = W_d d_e,\\ &W_d \propto (C_sC_p + C'_sC'_p)\cdot(\text{atomic matrix element for Pb}). && (5) \end{aligned}$$

In order to estimate W_d we have to fix all four parameters in Eqs. (3),(4). However, only three equations for these parameters are available. We can use:

- Isotopic shift for $X_0 - a_1$ transition
- HFS constant for a_1 level
- Second order spin-orbit (SO) splitting between a_1 and b_0

Using the Dirac-Fock values for all atomic matrix elements we get:

$$\begin{aligned} \text{IS:} \quad & (C'_s)^2 - (C_s)^2 = 0.18 & (6) \\ \text{HFS:} \quad & (C'_s)^2 + (C_s)^2 = 0.18 & (7) \\ \text{SO:} \quad & (C'_p)^2 \geq 0.08 & (8) \end{aligned}$$

The SO splitting between a_1 and b_0 gives only unequality because the energy of the level, which interacts with a_1 is not known.

If we take these equations literally, we get $C_s = 0$. Therefore, $W_d \propto C'_s C'_p$. Numerically that gives

$$|W_d| > 1 \cdot 10^{25} \text{ Hz/(e cm)}.$$

Comments

- *C'_p in (8) is rather small and it is possible that $C_p \gg C'_p$. Then, $C_s C_p$ in (5) can be of the same order as $C'_s C'_p$. Thus, we can not be sure that they do not cancel each other.*
- *The model can be tested if* **(i)** *dipole moments of the states X_0 and a_1 are measured (the model predicts that $D_X > D_a$), or* **(ii)** *G-factor for a_1 level is measured.*

Breit corrections to (binding) energies, hyperfine structure constants and E1 amplitudes for Cs. DFC denotes Dirac-Fock-Coulomb approximation; MBPT(v) and MBPT(c) correspond to the valence and core parts of the first order correction, while MBPT gives the final MBPT result. DFCB denotes Dirac-Fock-Coulomb-Breit approximation.

	DFC	MBPT(v)	MBPT(c)	MBPT	DFCB
$\varepsilon_{6s_{1/2}}$	0.127368	-0.000149		0.127217	0.127358
$\varepsilon_{6p_{1/2}}$	0.085616	-0.000079		0.085537	0.085577
$\varepsilon_{6p_{3/2}}$	0.083785	-0.000059		0.083726	0.083768
$\varepsilon_{7s_{1/2}}$	0.055187	-0.000041		0.055146	0.055183
$\varepsilon_{7p_{1/2}}$	0.042021	-0.000028		0.041993	0.042008
$\varepsilon_{7p_{3/2}}$	0.041368	-0.000021		0.041347	0.041362
$A_{6s_{1/2}}$	1423.8	-36.7	26.1	1413.1	1422.6
$A_{6p_{1/2}}$	160.9	-6.1	4.2	159.0	159.8
$A_{6p_{3/2}}$	23.9	-0.7	0.5	23.7	23.8
$A_{7s_{1/2}}$	391.2	-9.5	7.1	388.8	390.8
$A_{7p_{1/2}}$	57.6	-2.1	1.5	57.0	57.2
$A_{7p_{3/2}}$	8.6	-0.2	0.2	8.6	8.6
E1$(6s, 6p_{1/2})$	5.278	0.006		5.284	5.278
E1$(6s, 6p_{3/2})$	7.426	0.010		7.436	7.427
E1$(6s, 7p_{1/2})$	0.372	0.001		0.373	0.374
E1$(6s, 7p_{3/2})$	0.695	0.001		0.696	0.696
E1$(7s, 6p_{1/2})$	4.413	0.005		4.418	4.419
E1$(7s, 6p_{3/2})$	6.671	0.004		6.675	6.674
E1$(7s, 7p_{1/2})$	11.009	0.001		11.010	11.007
E1$(7s, 7p_{3/2})$	15.345	0.001		15.346	15.344

Calculations of the PNC amplitude $\langle 7s_{1/2}, m|\mathrm{E1}_{\mathrm{PNC}}|6s_{1/2}, m\rangle$ *for* $Q_W = -N$ *in the units* $i \cdot 10^{-11}$ *au. First contribution (*H_P*) is from the solution of the inhomogeneous equation with the right-hand-side* $H_P|6s_{1/2}, m\rangle$ *and the second contribution (E1) is from the solution of the inhomogeneous equation with the right-hand-side* $E1|6s_{1/2}, m\rangle$*.*

	(H_P)	(E1)	Total
Dirac-Fock-Brueckner with RPA	−.502	1.406	.904
Structural radiation	+.011	+.003	+.014
Normalization	+.004	−.011	−.007
Self-consistent Breit	+.002	−.006	−.004
This work (without Breit)	−.489	1.404	.911
This work (with Breit)	−.487	1.398	.907
Dzuba *et al* (without Breit)			.908
Blundell *et al* (without Breit)			.907
Blundell *et al* (with Breit)			.905

The most accurate measurement of $E1_{\mathrm{PNC}}$ was done in Boulder in 1997:

$$\frac{\mathrm{Im}E1_{\mathrm{PNC}}}{\beta} = -1.5939(56)\frac{\mathrm{mV}}{\mathrm{cm}},$$

where β is the Stark-induced amplitude:

$$\beta = 27.024(43)(67) \text{ au}$$

These results allow to test Standard model at low energies:

Experiment: $Q_W = -72.35(28)(34)$,
Standard model: $Q_W = -73.20(13)$,