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WHAT DO WE LEARN FROM ATOMIC PHYSICS ABOUT FUNDAMENTAL SYMMETRIES IN NUCLEI AND PARTICLES

BudkerINP 95-13

НОВОСИБИРСК

What do we Learn From Atomic Physics About Fundamental Symmetries in Nuclei and Particles

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Abstract

Atomic experiments bring meaningful and valuable information on fundamental symmetries. The hypothesis of a large ($\sim$ 100 eV) P-odd weak matrix element between single-particle states in heavy nuclei is inconsistent with the results of atomic PNC experiments. Upper limits on CP-violation obtained in atomic and molecular spectroscopy are as informative as those established in neutron physics. Very strict upper limits on T-odd, P-even interactions (nucleon-nucleon, electron-nucleon, electron-electron, and β-decay) are derived from the same atomic and neutron experiments.

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1. The scattering cross-sections of longitudinally polarized epithermal (1 - 1000 eV) neutrons from heavy nuclei at $p_{1/2}$ resonances have large longitudinal asymmetry. For a long time the most natural explanation of the effect was based on the statistical model of the compound nuclei. In fact, not only the explanation, but the very prediction of the huge magnitude of this asymmetry (together with the nuclei most suitable for the experiments) was made theoretically on the basis of this model [1].

An obvious prediction of the statistical model is that after averaging over resonances, the asymmetry should vanish. However, few years ago it was discovered [2] that all seven asymmetries measured in ^{232}Th have the same, positive sign.

All the attempts [3 - 7] to explain a common sign require the magnitude of the weak interaction matrix element, mixing opposite-parity nuclear levels, to be extremely large,
$\sim$ 100 eV. [2] The same assumption seems to be necessary to explain unexpectedly large P-odd correlations observed in Mössbauer transitions in ^{119}Sn and ^{57}Fe [9, 10].

In Ref. [11] it was pointed out that such a large magnitude of the weak mixing can be checked in an independent experiment. The proposal is to measure PNC asymmetry in the M4 γ-transition between the (predominantly) single-particle states $1i\ 13/2^+$ and $2f\ 5/2^-$ in ^{207}Pb. The sensitivity of this experiment to the weak matrix element value is expected to reach $5 - 13$ eV.

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[2] The only exception known to me is recent paper [8] where large octupole deformation of nucleus is discussed as a possible explanation of this regularity.

However, it was demonstrated recently [12] that close upper limit on the weak mixing in ^{207}Pb can be extracted already now from the measurements of the PNC optical activity of atomic lead vapour. The following upper limit was established at the 95% confidence level for the ratio of the nuclear-spin-dependent (NSD) part of the optical activity to the main, nuclear-spin-independent one [13]:

$$\frac{P_{NSD}}{P} < 0.02 \tag{1}$$

In heavy atoms the NSD P-odd effects were shown to be induced mainly by contact electromagnetic interaction of electrons with the anapole moment of a nucleus which is its P-odd electromagnetic characteristic induced by PNC nuclear forces [14, 15]. The result (1) leads to the following bound on the dimensionless anapole constant: $\kappa(^{207}Pb) < 1$, and on the effective neutron PNC constant: $g_n < 10$. The last constant is introduced via the effective P-odd potential for an external nucleon:

$$W = \frac{G}{\sqrt{2}}\,\frac{g}{2m}\,\vec{\sigma}[\vec{p}\rho(r) + \rho(r)\vec{p}\,]. \tag{2}$$

Here $G = 1.027 \cdot 10^{-5} m^{-2}$ is the Fermi weak interaction constant, m is the proton mass, $\vec{\sigma}$ and $\vec{p}$ are respectively spin and momentum operators of the valence nucleon, $\rho(r)$ is the density of nucleons in the core normalized by the condition $\int d\vec{r}\rho(r) = A$ (the atomic number is assumed to be large, $A \gg 1$).

At $g_n < 10$ a simple-minded estimate for a typical weak mixing matrix element is:

$$\langle W \rangle < 20\, eV \tag{3}$$

More sophisticated calculations based on a Woods-Saxon potential with the spin-orbit interaction produce the following upper limit on the concrete matrix element of interest for the proposed experiment with ^{207}Pb:

$$\langle 3d\, 5/2^{+}|W|2f\, 5/2^{-}\rangle < 14\, eV. \tag{4}$$

It is close to the expected accuracy of the experiment discussed in Ref. [11]. Of course, this experiment still would be both interesting and informative, so much the more that it would be the first occasion when PNC effects in the same nucleus were measured both in atomic and nuclear experiments.

However, as to the hypothesis itself, according to which the value of the weak mixing matrix element is as high as 100 eV, such a large its value does not agree with the results of the atomic PNC experiments.

2. Up to now CP-violation has been observed in K-meson decays only. One more source of the information on this phenomenon are the upper limits on electric dipole moments (EDM) established both in the neutron experiments and in atomic and molecular spectroscopy: due to them a lot of models of CP-violation have been ruled out. The best experimental upper limit on the neutron EDM $d(n)$ (the combined result of Refs. [16, 17]) is:

$$d(n)/e < 7 \cdot 10^{-26}\, cm. \tag{5}$$

Impressive results for the electron EDM were obtained in experiments with paramagnetic atoms, cesium [18] and thallium [19]. In particular, the thallium experiment resulted in

$$d(e)/e = (1.8 \pm 1.2 \pm 1.0) \cdot 10^{-27}\, cm. \tag{6}$$

In the standard model the neutron EDM arises to second order in G only and is therefore very small. It is controlled by long-distance contributions and constitutes [20]

$$d(n)/e \sim 10^{-32} - 10^{-31}\, cm. \tag{7}$$

(The estimate given in Ref. [21] is an order of magnitude larger.) Even more tiny is the electron EDM in the standard model:

$$d(e)/e < 10^{-40}\, cm. \tag{8}$$

The highest absolute precision has been achieved in experiments with diamagnetic atoms and molecules, mercury and thallium fluoride. A record-breaking upper limit on electric dipole moment of anything was reported in [22]. The measurements of atomic EDM of the mercury isotope ^{199}Hg result in

$$d(^{199}Hg)/e < 9.1 \cdot 10^{-28}\, cm. \tag{9}$$

Still, the upper limit on the neutron EDM following from (9)

$$d(n)/e < 6 \cdot 10^{-25}\, cm \tag{10}$$

is an order of magnitude worse than the direct one (5).

However, CP-odd nuclear forces are much more effective in inducing nuclear dipole moments than neutron or proton EDM [23]. Let us present the effective CP-odd interaction of the external nucleon with nuclear core as

$$W = \frac{G}{\sqrt{2}}\,\frac{\xi}{2m}\,\vec{\sigma}\,\vec{\nabla}\rho(r) \tag{11}$$

where ξ is its dimensionless characteristic. Then the experimental limit (9) corresponds to

$$\xi < 1.7 \cdot 10^{-3}. \tag{12}$$

It looks to be a serious challenge to reach a comparable accuracy in neutron scattering experiments.

But again the standard model prediction for the constant ξ does not exceed 10^{-9}. Taken together with the standard model predictions for the neutron and electron EDMs, does not it mean that the experiments discussed in this section are of no serious interest for the elementary particle physics, are nothing else but mere exercises in precision spectroscopy?

Just the opposite. It means that these experiments now, at the present level of accuracy are extremely sensitive to possible new physics beyond the standard model, physics which does not manifest in the kaon decays. Since various models of CP-violation have as a rule too many degrees of freedom, it is natural to present the implications of the neutron and atomic experiments in a purely phenomenological way: to construct CP-odd quark-quark, quark-gluon and gluon-gluon operators of low dimension, and find upper limits from those experiments on the corresponding coupling constants [24]. The results are given in Table 1

$k_i O_i$	$d(n)/e < 7 \cdot 10^{-26}$cm	$d(^{199}Hg)/e < 9 \cdot 10^{-28}$cm
$k_s(\bar{q_1} i\gamma_5 q_1)(\bar{q_2} q_2)$	$\lvert k_s\rvert < 2 \cdot 10^{-5}$	$\lvert k_s\rvert < 2 \cdot 10^{-6}$
$k_s^c(\bar{q_1} i\gamma_5 t^a q_1)(\bar{q_2} t^a q_2)$		
$q_1 = q_2$	$\lvert k_s^c\rvert < 7 \cdot 10^{-5}$	$\lvert k_s^c\rvert < 7 \cdot 10^{-6}$
$q_1 \neq q_2$	$\lvert k_s^c\rvert < 7 \cdot 10^{-5}$	$\lvert k_s^c\rvert < 6 \cdot 10^{-4}$
$k_t(1/2)\epsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}u)(\bar{d}\sigma_{\alpha\beta}d)$	$\lvert k_t\rvert < 8 \cdot 10^{-6}$	$\lvert k_t\rvert < 7 \cdot 10^{-5}$
$k_t^c(1/2)\epsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}t^a u)(\bar{d}\sigma_{\alpha\beta}t^a d)$	$\lvert k_t^c\rvert < 6 \cdot 10^{-6}$	$\lvert k_t^c\rvert < 5 \cdot 10^{-5}$
$k_q^g\, m_p\, \bar{q}\gamma_5\sigma_{\mu\nu} g G^a_{\mu\nu} t^a q$	$\lvert k_q^g\rvert < 2 \cdot 10^{-7}$	$\lvert k_q^g\rvert < 4 \cdot 10^{-8}$
$k^g(1/6)\epsilon_{\mu\nu\alpha\beta} f^{abc} G^a_{\mu\nu} G^b_{\alpha\rho} G^c_{\beta\rho}$	$\lvert k^g\rvert < 3 \cdot 10^{-5}$	$\lvert k^g\rvert < 3 \cdot 10^{-4}$
$\theta(\alpha_s/8\pi)(1/2)\epsilon_{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$	$\lvert\theta\rvert < 2 \cdot 10^{-10}$	$\lvert\theta\rvert < 7 \cdot 10^{-10}$

Table 1

where the limits on the dimensionless constants k_i of effective operators

$$\frac{G}{\sqrt{2}} \sum_i k_i O_i$$

for the CP-odd interaction of u-, d-quarks and gluons are presented [25]. Some upper limits following from the atomic experiment have been derived from the bound (10) extracted from the same mercury result.

Clearly, the neutron and atomic experiments are complementary to each other. Some effective constants are bounded by them on the "microweak" level or even better.

3. Direct experimental information on the T-odd, P-even (TOPE) interactions is rather poor. Best limits on the relative magnitude of the corresponding admixtures to nuclear forces lie around 10^{-3}. We will relate again all interactions to the Fermi weak interaction constant G. Since the nuclear scale of weak interactions is $Gm_\pi^2 \sim 2 \cdot 10^{-7}$, those limits can be formulated as $10^4 G$. Direct experimental limits on various TOPE interactions, together with proposals, and new limits obtained in Refs. [26 - 28], are presented in Table 2.

	NN	eN	β-decay
direct limits	$< 10^4 G$		$< 0.5,\ < 10^{-3}$
proposals	$< 10G$	$< 10^4 G$	$< 10^{-3}$
new limits	$< 10^{-4} G$	$< 10^{-4} G$	$Im\,(C_S + C'_S) < 4 \cdot 10^{-3}$ $Im\,(C_T + C'_T) < 5 \cdot 10^{-4}$ $Im\,(C_P + C'_P) < 0.3$

Table 2

Let us point out first of all that the predictions of all modern renormalizable theories of CP-violation (and not only the standard model!) cannot exceed $(10^{-3} - 10^{-4})\,G$. The reason is obvious. Parity violation is an intrinsic property of all these models, and therefore T-odd, P-even effects should be roughly of the same order of magnitude as T-odd, P-odd ones. And again, in no way does it mean by itself that the experimental efforts in this field do not make sense. They do, but it should be understood clearly that this is the search for essentially new physics, well beyond the modern theories.

The approach adopted in Ref. [26] consisted in combining phenomenological TOPE 4-fermion operators with P-odd part of the electroweak radiative corrections. These one-loop short-distance corrections generate T- and P-odd 4-fermion operators. Upper limits on the corresponding effective constants are extracted from the bounds on the neutron and atomic dipole moments. In this way one gets for different TOPE constants the upper limits on the level

$$(1 - 10)\, G. \tag{13}$$

The estimates performed independently by M.G. Kozlov and myself (cited in Ref. [26]) show that the account for the long-distance effects in the interplay of the usual neutral-current weak interaction and the discussed TOPE one leads to limits weaker than (13) obtained via the short-distance mechanism. The result of recent elaborate papers [29 - 31] consists in fact in the same conclusion.

Much better than (13) limits presented in Table 2 were obtained in Ref. [28] by calculating in two-loop approximation directly electron and quark dipole moments (instead of effective T- and P-odd 4-fermion operators) [3].

At last some information can be obtained in an analogous way concerning even β-decay constants [26, 27]. To relate them to the eN TOPE interaction one should evidently switch on the W-exchange. Unfortunately, this procedure is more ambiguous than the switching on Z-exchange used in our previous consideration.

One-loop approach leads here to the limits on the T-odd scalar, tensor and pseudoscalar constants presented in Table 2. The two-loop approximation leads to the limits on the T-odd part of β-decay interaction with derivatives on the level [27]

$$10^{-4}\, G. \tag{14}$$

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[3] One cannot exclude of course the possibility that the contributions of various particles to the two-loop diagrams discussed cancel out. This possibility emphasized in Ref. [30] refers obviously to any estimates (including certainly those of Ref. [30] itself) made in a field where no reliable theory exists. As to the analogy with the well-known GIM mechanism mentioned in [30], it does not look relevant here. The reasons for the GIM cancellation in the standard model are well-known, but what have they to do with the discussed nonrenormalizable TOPE interactions?

References

[1] O.P. Sushkov, V.V. Flambaum: Pis'ma Zh.Eksp.Teor.Fiz. **32** (1980) 377 [Sov.Phys.JETP Lett **32** (1980) 353]

[2] C.M. Frankle, J.D. Bowman, J.E. Bush, P.P.J. Delheij, C.R. Gould, D.G. Haase *et al.*: Phys.Rev.Lett. **67** (1991) 564; Phys.Rev.C **46** (1992) 778

[3] V.V. Flambaum: Phys.Rev. C **45** (1992) 437

[4] J.D. Bowman, G.E. Garvey, C.R. Gould, A. Hayes, M.B. Johnson: Phys.Rev.Lett. **68** (1992) 780

[5] S.E. Koonin, C.W. Johnson, P. Vogel: Phys.Rev.Lett. **69** (1992) 1163

[6] N. Auerbach, J.D. Bowman: Phys.Rev. C **46** (1992) 2582

[7] C.H. Lewenkopf, H.A. Weidenmüller: Phys.Rev. C **46** (1992) 2601

[8] V.V. Flambaum, V.G. Zelevinsky: Preprint MSUCL-963, December 1994; submitted to Phys.Lett. B

[9] L.V. Inzhechik, E.V. Mel'nikov, A.S. Khlebnikov, V.G. Tsinoev, B.J. Ragozev: Zh.Eksp.Teor.Fiz. **93** (1987) 800 [Sov.Phys. JETP **66** (1987) 450]; Yad.Fiz. **44** (1986) 1370 [Sov.J.Nucl.Phys. **44** (1986) 890]

[10] L.V. Inzhechik, A.S. Khlebnikov, V.G. Tsinoev, B.J. Ragozev, M.Yu. Silin, Yu.M. Pen'kov: Zh.Eksp.Teor.Fiz. **93** (1987) 1560 [Sov.Phys. JETP **66** (1987) 897]

[11] J.J. Szymansky, J.D. Bowman, M. Leuschner, B.A. Brown, I.C. Girit: Phys.Rev. C **49** (1994) 3297

[12] V.F. Dmitriev, I.B. Khriplovich, V.B. Telitsin: Preprint BINP 94-98, December 1994; submitted to Phys.Rev. C

[13] D.M. Meekhof, P. Vetter, P.K. Majumder, S.K. Lamoreaux, E.N. Fortson: Phys.Rev.Lett. **71** (1993) 3442

[14] V.V. Flambaum, I.B. Khriplovich: Zh.Eksp.Teor.Fiz. **79** (1980) 1656 [Sov.Phys. JETP **52** (1980) 835]

[15] V.V. Flambaum, I.B. Khriplovich, O.P. Sushkov: Phys.Lett. **B145** (1984) 367

[16] K.F. Smith *et al.*: Phys.Lett. B **234** (1990) 191

[17] I.S. Altarev *et al.*: Phys.Lett. B **276** (1992) 242

[18] L.R. Hunter: *in* Proceedings of the International Conference: Neutral Currents Twenty Years Later, ed. U. Nguyen-Khac and A.M. Lutz (World Scientific, Singapore, 1993), p. 271

[19] E.D. Commins, S.B. Ross, D. DeMille, B.C. Regan: Phys.Rev. A, to be published

[20] I.B. Khriplovich, A.R. Zhitnitsky: Phys.Lett. B **109** (1982) 490

[21] M.B. Gavela, A. Le Yaouanc, L. Oliver, O. Pène, J.-C. Raynal, T.N. Pham: Phys.Lett. B **109** (1982) 215

[22] W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, E.N. Fortson, J.P. Jacobs: Phys.Rev. A, to be published

[23] O.P. Sushkov, V.V. Flambaum, I.B. Khriplovich: Zh.Eksp.Teor.Fiz. **87** (1984) 1521 [Sov.Phys. JETP **60** (1984) 873]

[24] V.M. Khatsymovsky, I.B.Khriplovich, A.S. Yelkhovsky: Ann.Phys. **186** (1988) 1

[25] V.M. Khatsymovsky, I.B.Khriplovich: Phys.Lett. B **296** (1992) 219

[26] I.B. Khriplovich: Nucl.Phys. B **352** (1991) 385

[27] I.B. Khriplovich: Pis'ma Zh.Eksp.Teor.Fiz. **52** (1990) 1065 [Sov.Phys.JETP Lett. **52** (1990) 461]

[28] R.S.Conti, I.B. Khriplovich: Phys.Rev.Lett. **68** (1992) 3262

[29] W.C. Haxton, A. Höring: Nucl.Phys. A **560** (1993) 469

[30] W.C. Haxton, A. Höring, M. Musolf: Phys.Rev. D **50** (1994) 3422

[31] J. Engel, C.R. Gould, V. Hnizdo: Phys.Rev.Lett. **73** (1994) 3508

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BudkerINP 95-13

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**Что известно из ядерной физики
о фундаментальных симметриях в ядрах и частицах?**

Ответственный за выпуск С.Г. Попов
Работа поступила 8 февраля 1995 г.

Сдано в набор 13 февраля 1995 г.
Подписано в печать 13 февраля 1995 г.
Формат бумаги 60×90 1/16 Объем 0.7 печ.л., 0.6 уч.-изд.л.
Тираж 160 экз. Бесплатно. Заказ N° 13

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.