Electric dipole moments, present and future[1]

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Upper limits on the electric dipole moments (EDM) of elementary particles and atoms are presented, and their physical implications are discussed. The bounds following from the neutron and atomic experiments are comparable. In particular, they strongly constrain P odd, T even interactions. The nuclear EDMs can be studied at ion storage rings, with the expected sensitivity much better than 10^{-24} e cm. It would be a serious progress in the studies of the CP violation.

1. UPPER LIMITS ON ELECTRIC DIPOLE MOMENTS

Up to now CP violation has been reliably observed only in the decays of the K^0 mesons. Recently, indications of CP violations were found in $B_d^0/\bar{B}_d^0 \to J/\psi K_S^0$ decays. Though the effects observed can be accomodated within the Standard Model, their true origin still remains mysterious.

Extremely important information on the origin of CP violation follows from the searches for electric dipole moments of the neutron, electron and atoms. The EDM of a nondegenerate quantum-mechanical system is forbidden by time-reversal symmetry T (and by parity conservation). T invariance and CP invariance are equivalent, due to the CPT theorem, which is based on very strong physical grounds. Detailed discussion of discrete symmetries (as well as of other problems touched upon in the talk) can be found, for instance, in book [1].

1.1 Elementary particles

The experimental upper limit on the neutron EDM is [2-4]

$$d_{\mathrm{n}} < (6-10) \times 10^{-26}\, e\,\mathrm{cm}. \tag{1}$$

The sensitivity of these experiments can be, hopefully, improved by 2 – 3 orders of magnitude.

The best upper limit on the electron EDM

$$d_{\mathrm{e}} < 4 \times 10^{-27}\, e\,\mathrm{cm} \tag{2}$$

was obtained in atomic experiment with Tl [5]. Hopefully, this limit can be pushed well into the 10^{-28} $e\,$cm range.

I would like to quote here one more upper limit, that on the muon EDM [6]:

$$d_\mu < 10^{-18}\, e\,\mathrm{cm}. \tag{3}$$

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An experiment was recently proposed to search for the muon EDM with the sensitivity of 10^{-24} $e\,$cm [7]. We will come back to this proposal in Section 3.

The predictions of the Standard Model are, respectively:

$$d_{\rm n} \sim 10^{-32} \ - \ 10^{-31}\ e\,{\rm cm}; \tag{4}$$

$$d_{\rm e} < 10^{-40}\ e\,{\rm cm}; \tag{5}$$

$$d_{\mu} < 10^{-38}\ e\,{\rm cm}. \tag{6}$$

1.2 Atoms and nuclei

The best upper limit on EDM of anything was obtained in atomic experiment with ^{199}Hg [8]. The result for the dipole moment of this atom is

$$d(^{199}{\rm Hg}) < 9\times 10^{-28}\ e\,{\rm cm}. \tag{7}$$

Unfortunately, due to the electrostatic screening of the nuclear EDM in this essentially Coulomb system, the implications of the result (7) are somewhat less impressive. If one ascribes the atomic dipole moment to the EDM of the valence neutron in the even-odd nucleus ^{199}Hg, the corresponding upper limit on the neutron EDM will be an order of magnitude worse than the direct one (1).

It has been demonstrated, however, that the dipole moments of *nuclei* induced by the T- and P-odd nuclear forces can be about two orders of magnitude larger than the dipole moment of an individual *nucleon* [9]. In the simplest approximation of the shell model, where the nuclear spin coincides with the total angular momentum of an odd valence nucleon, while the other nucleons form a spherically symmetric core with the zero angular momentum, the effective T- and P-odd single-particle potential for the outer nucleon is

$$W \;=\; \frac{G}{\sqrt{2}}\,\frac{\xi}{2m_p}\,\boldsymbol{\sigma}\,\boldsymbol{\nabla}\rho(r)\,. \tag{8}$$

Here ξ is a dimensionless constant characterizing the strength of the interaction in units of the Fermi weak interaction constant G; $\boldsymbol{\sigma}$ and $\mathbf{r}$ are the spin and coordinate of the valence nucleon. Using the fact that the profiles of the nuclear core density $\rho(r)$ and the potential $U(r)$ are close, one can easily find now the perturbation of the wave function caused by the interaction (8). The characteristic value of the thus induced nuclear EDM is

$$d_{\rm N} \sim\ 10^{-21}\,\xi\ e\,{\rm cm}. \tag{9}$$

Being interpreted in terms of the CP-odd nuclear forces, the experimental result (7) leads to the following upper limit:

$$\xi < 2\times 10^{-3}. \tag{10}$$

The Standard Model (SM) prediction for this constant is

$$\xi \sim 10^{-9}. \tag{11}$$

Thus, the theoretical predictions of the SM for dipole moments and CP-odd nuclear forces are about six orders of magnitude below the present experimental upper limits on them. But does this mean that the discussed experiments are of no serious interest for elementary particle physics, that they are nothing but mere exercises in precision spectroscopy? Just the opposite. It means that *the searches for electric dipole moments now, at the present level of accuracy, are extremely sensitive to possible new physics.*

1.3 Beyond the Standard Model

One could argue that the discussed experiments have ruled out more theoretical models than any other set of experiments in the history of physics. Still, theoretical models of CP violation surviving up to now, are to numerous to discuss all of them, and most of them have too many degrees of freedom. It is convenient therefore to proceed in a phenomenological way: to construct CP-odd quark-quark, quark-gluon and gluon-gluon operators of low dimension, and find upper limits on the corresponding coupling constants from the experimental results for $d_{\rm n}$ and $d(^{199}\mathrm{Hg})$. The analysis performed in [10,11], has demonstrated that the limits on the effective CP-odd interaction operators obtained from the neutron and atomic experiments are quite comparable. These limits are very impressive. All the constants are several orders of magnitude less than the usual Fermi weak interaction constant G. In particular, these limits strongly constrain some popular models of CP violation, such as the model of spontaneous CP violation in the Higgs sector, and the model of CP violation in the supersymmetric SO(10) model of grand unification.

2. T ODD, P EVEN ASIDE

The EDM experiments lead also to strict upper limits on the T odd, P even (TOPE) interactions.

Best direct upper limit on TOPE admixture in nuclear forces is

$$\alpha_T < 10^{-3}. \tag{12}$$

In any renormalizable model this admixture is at least seven orders of magnitude smaller than (12). Moreover, the effect never arises to second order in the semiweak coupling [12]. Therefore, searches for the TOPE interactions are searches for new physics.

To obtain bounds on TOPE interactions from the EDM experiments, we have to combine this interaction with P odd electroweak correction. A simple estimate for the thus induced neutron EDM is [13,14]

$$d_{\rm n} \sim \frac{1}{m_p}\,(Gm_\pi^2)\,\alpha_T < 10^{-25}\ e\,\mathrm{cm}, \tag{13}$$

which gives

$$\alpha_T < 10^{-4}. \tag{14}$$

Numerous elaborations on this "long-distance" estimate (see, for instance, [15]) are of a certain interest for theoretical nuclear physics, but none of them resulted in a serious improvement over the simple-minded result (14).

The true improvement is reached by going over to short-distance effects. The corresponding contribution to the neutron EDM, due to a phenomenological TOPE interaction and the P odd electroweak one, both being combined into a two-loop diagram, results in an extremely strong upper limit [16]:

$$\alpha_T < 10^{-12}. \tag{15}$$

Quite recently objections were made in [17] against the approach of [16]. In view of the importance of the result (15), it seems appropriate to discuss these objections.

1. It is argued in [17] that our calculation "relies on an erroneous result for the one-loop subgraph associated with the ABJ (chiral) anomaly".

In fact, an identity is overlooked in [17],

$$A^{\mu\lambda\alpha} + B^{\mu\lambda\alpha} + C^{\mu\lambda\alpha} = 0$$

(in the notations of [17]), which reduces the corresponding result of [17] to ours.

2. In [17], the dimensional regularization (DR) is advocated against our estimates with a cut-off.

However, in the discussed problem, the adopted in [17] DR (which kills the powerlike divergence of the diagrams discussed) is nothing but an accurate calculation of a small contribution of large distances, while in [16] the estimate is made of the dominating contribution of short distances.

Thus, there are no reasons to doubt the validity of the result (15).

3. NUCLEAR ELECTRIC DIPOLE MOMENTS AT ION STORAGE RINGS

The various upper limits on EDMs set so far constitute a valuable contribution to elementary particle physics and to our knowledge of how the Nature is arranged; the null results obtained so far are important. But it is only natural to think of essential progress in the field, of finding a positive result, of eventually discovering permanent electric dipole moment. So, let me add to the above rather old stories, a new one. It should be started with the discussion of

3.1 Idea of new muon EDM experiment

A new experiment was recently proposed to search for the muon EDM [7]. The intention is to use a storage ring, with muons in it having natural longitudinal polarization. An additional spin precession due to the EDM interaction with external field should be monitored by counting the decay electrons, their momenta being correlated with the muon spin, due to parity nonconservation in the muon decay.

The frequency $\boldsymbol{\omega}$ of the spin precession with respect to the particle momentum in external magnetic and electric fields, $\mathbf{B}$ and $\mathbf{E}$, is

$$\boldsymbol{\omega} = -\frac{e}{m}\left[a\mathbf{B} - a\,\frac{\gamma}{\gamma+1}\,\mathbf{v}\,(\mathbf{vB}) - \left(a - \frac{1}{\gamma^2-1}\right)\mathbf{v}\times\mathbf{E}\right] \qquad (16)$$

$$-\,\eta\,\frac{e}{m}\left[\mathbf{E} - \frac{\gamma}{\gamma+1}\,\mathbf{v}\,(\mathbf{vE}) + \mathbf{v}\times\mathbf{B}\right].$$

Here the anomalous magnetic moment a is related to the g-factor as follows: $a = g/2 - 1$ (for muon $a = \alpha/2\pi$); $\mathbf{v}$ is the particle velocity; $\gamma = 1/\sqrt{1-v^2}$. The last line in this formula describes the precession due to the EDM d, the dimensionless constant η being related to d as follows:

$$d = \frac{e}{2m}\,\eta$$

Expression (16) simplifies in the obvious way for $(\mathbf{vB}) = (\mathbf{vE}) = 0$. Just this case is considered below.

The remarkable idea of [7] is to compensate for the usual precession in the vertical magnetic field $\mathbf{B}$ by the precession in a radial electric field $\mathbf{E}$, i.e., to choose $\mathbf{E}$ in such a way that the first line in (16) vanishes at all. Then the spin precession with respect to momentum is due only to the EDM interaction with the vertical magnetic field, and since electric fields in a storage ring are much smaller than magnetic ones, it reduces to

$$\boldsymbol{\omega} = \boldsymbol{\omega}_e = -\frac{e}{m}\,\eta\,\mathbf{v}\times\mathbf{B}. \qquad (17)$$

In this way the muon spin acquires a vertical component which linearly grows with time. The P-odd correlation of the decay electron momentum with the muon spin leads to the difference between the number of electrons registered above and below the orbit plane.

In [7], it is stated that the limit on the muon EDM can be improved in the planned experiment by six orders of magnitude, to 10^{-24} e cm.

3.2 Nuclear dipole moments at storage rings

In the same way one can search for an EDM of a polarized β-active nucleus in a storage ring [18]. In this case as well, the precession of nuclear spin due to the EDM interaction can be monitored by the direction of the β-electron momentum.

β-active nuclei have serious advantages as compared to muon. The life-time of a β-active nucleus can exceed by many orders of magnitude that of a muon. The characteristic depolarization time of the ion beam is also much larger than the muon life-time, which is about 10^{-6} s. According to the estimates by I. Koop (to be published), the ion depolarization time can reach few seconds. Correspondingly, the angle of the rotation of nuclear spin, which is due to the EDM interaction and which accumulates with time, may be also by orders of magnitude larger than that of a muon. By the same reason of the larger life-time, the quality of an ion beam can be made much better than that of a muon beam.

However, necessary conditions here are also quite serious.

First of all, to make realistic the mentioned compensation of the EDM-independent spin precession by a relatively small electric field, the effective nuclear g-factor should be close to 2 (as this is the case for the muon). For a nucleus with the total charge Ze, mass Am_p, spin I, and magnetic moment μ, the effective anomalous magnetic moment is now

$$a = \frac{g}{2} - 1 = \frac{A}{Z}\,\frac{\mu}{2\mathrm{I}} - 1.$$

Fine-tuning of a is possible in many cases by taking, instead of a bare nucleus, an ion with closed electron shells. An accurate formula for the anomaly of an ion with the total charge z, is

$$a = \frac{A}{2z}\,\frac{\mu}{\mathrm{I}} - 1.00722 + \frac{\Delta}{Am_p} - \frac{z}{A}\,\frac{m_e}{m_p}. \tag{18}$$

As distinct from [18], we have included here the correction for the atomic mass excess Δ.

The ions which look at the moment promising from the point of view of the EDM searches are presented in Tables 1, 2. The isotope data are taken from the handbook [19]. The β-decaying excited states are marked in Table 1 by *.

Table 1: Ion properties

	$\mathrm{I}^\pi \to \mathrm{I}^{\pi\,\prime}$	μ	z	$a \times 10^3$	$t_{1/2}$	Q (barn)	branching
$^{24}_{11}$Na	$4^+ \to 4^+$	1.6903(8)	5	6.5(0.5)	15 h		99.944%
$^{60}_{27}$Co	$5^+ \to 4^+$	3.799(8)	23	- 17(2)	5.3 y	0.44	99.925%
$^{82}_{35}$Br	$5^- \to 4^-$	1.6270(5)	13	18.0(0.3)	35 h	0.75	98.5%
$^{94}_{37}$Rb	$3^- \to 3^-$	1.4984(18)	23	12.5(1.2)	2.7 s	0.16	30.6%
$^{110}_{47}$Ag*	$6^+ \to 5^+$	3.607(4)	33	- 6(1)	250 d	1.4	66.8%
$^{118}_{49}$In*	$8^- \to 7^-$	3.321(11)	25	- 28(3)	8.5 s	0.44	1.4%
$^{120}_{49}$In*	$(8^-) \to 7^-$	3.692(4)	27	17(1)	47 s	0.53	84.1%
$^{121}_{50}$Sn	$3/2^+ \to 5/2^+$	0.6978(10)	28	2.9(1.4)	27 h	- 0.02(2)	100%
$^{125}_{51}$Sb	$7/2^+ \to 5/2^+$	2.630(35)	47	- 9.0(1.3)	2.8 y		40.3%
$^{131}_{53}$I	$7/2^+ \to 5/2^+$	2.742(1)	51	- 1.9(0.4)	8.0 d	- 0.40	89.9%
$^{133}_{53}$I	$7/2^+ \to 5/2^+$	2.856(5)	53	16(2)	21 h	- 0.27	83%
$^{133}_{54}$Xe	$3/2^+ \to 5/2^+$	0.81340(7)	36	- 6.37(9)	5.2 d	0.14	99%
$^{134}_{55}$Cs	$4^+ \to 4^+$	2.9937(9)	51	- 24.9(0.3)	2.0 y	0.39	70.11%
$^{136}_{55}$Cs	$5^+ \to 6^+$	3.711(15)	51	- 18(4)	13 d	0.22	70.3%
$^{137}_{55}$Cs	$7/2^+ \to 11/2^-$	2.8413(1)	55	3.0(0.1)	30 y	0.051	94.4%

Table 2: Ion properties (continued)

	$I^\pi \to I^{\pi\,\prime}$	μ	z	$a \times 10^3$	$t_{1/2}$	Q (barn)	branching
$^{139}_{55}$Cs	$7/2^+ \to 7/2^-$	2.696(4)	53	2(1)	9.3 m	- 0.075	82%
$^{141}_{55}$Cs	$7/2^+ \to 7/2^-$	2.438(10)	49	- 6(4)	25 s	- 0.36	57%
$^{143}_{55}$Cs	$3/2^+ \to 5/2^-$	0.870(4)	41	3(5)	1.8 s	0.47	24%
$^{140}_{57}$La	$3^- \to 3^+$	0.730(15)	17	- 6±21	1.7 d	0.094	44%
$^{160}_{65}$Tb	$3^- \to 2^-$	1.790(7)	47	8(4)	72 d	3.8	44.9%
$^{170}_{69}$Tm	$1^- \to 0^+$	0.2476(36)	21	- 5±14	129 d	0.74	99.854%
$^{177}_{71}$Lu	$7/2^+ \to 7/2^-$	2.239(11)	57	- 15(5)	6.7 d	3.4	78.6%
$^{183}_{73}$Ta	$7/2^+ \to 7/2^-$	(+)2.36(3)	61	4±13	5.1 d		92%
$^{196}_{79}$Au	$2^- \to 2^+$	0.5906(5)	29	- 9.5(0.8)	6.2 d	0.81	8%
$^{198}_{79}$Au	$2^- \to 2^+$	0.5934(4)	29	5.4(0.7)	2.7 d	0.68	98.99%
$^{203}_{80}$Hg	$5/2^- \to 3/2^+$	0.84895(13)	34	6.31(0.15)	47 d	0.34	100%
$^{222}_{87}$Fr	$2^- \to 3^-$	0.63(1)	35	- 8± 16	14 m	0.51	55%
$^{223}_{87}$Fr	$3/2^{(-)} \to 3/2^-$	1.17(2)	87	- 7±20	22 m	1.2	67%
$^{224}_{87}$Fr	$1^{(-)} \to 1^-$	0.40(1)	45	- 11± 25	3.3 m	0.52	42%
$^{242}_{95}$Am	$1^- \to 0^+, 2^+$	0.3879(15)	47	- 8.4± 3.9	16 h	- 2.4	37%,46%

The errors in the values of anomalous magnetic moments a, presented in Tables 1, 2, correspond to the experimental errors in values of μ. In fact, electron configurations, even with vanishing angular momentum J_e, produce a diamagnetic screening of nuclear magnetic moments. In most cases this correction, neglected here, is inessential indeed, but it is truly large for $^{24}_{11}$Na, changing its a-value from 0.0065, as presented in Table 1, to about - 0.1.

All isotopes presented in Tables 1, 2 are β^--active (their β^- branchings are indicated in the last column). Fortunately, many of them have allowed pure Gamow – Teller transitions ($|\Delta I| = 1$) where the magnitude of the needed correlation between the electron momentum and the initial spin is on the order of unity. Few isotopes in the tables have allowed mixed β^--transitions ($|\Delta I| = 0$). Here the magnitude of the needed asymmetry may change essentially from nucleus to nucleus. Obviously, for the allowed mixed transitions, as well as for forbidden transitions which are also presented in the tables, the values of the discussed asymmetry should be found experimentally.

On the other hand, if a sufficiently large EDM signal can be attained, if the angle of the spin rotation can reach, say, a milliradian, one could think about an experiment with stable nuclei or nuclei of a large life-time. Their polarization could be measured in scattering experiments (the idea advocated by Y. Semertzidis and A. Skrinsky). Among stable nuclei, the most suitable one seems to be ${}^{139}_{57}$La, with $a = -0.039$ for the bare nucleus and $a = -0.004$ for its helium-like ion.

The nuclear polarization can be obtained, for instance, starting with a hydrogen-like ion. For $Z \sim 50$, typical frequencies of hyperfine ground state transitions in these ions are close to the optical region. The ion can be polarized by optical pumping, and then stripped. A helium-like ion with polarized nucleus can be obtained from a polarized hydrogen-like one through the electron capture.

In principle, the demand $a \ll 1$ can be softened by going over to small velocities, $v/c \ll 1$. This would enhance the relative weight of the compensating electric field. However, in this case one looses in the magnitude of the EDM signal.

But how significant would be the discussed experiments with nuclei for elementary particle physics?

The typical value of a nuclear EDM, as induced by CP-odd nuclear forces, is roughly independent of A and Z, and can be estimated by formula (9). The upper limit (10) on ξ corresponds to the bound

$$d_{\mathrm{N}} < 2 \times 10^{-24}\, e\,\mathrm{cm}, \tag{19}$$

and is at least as significant for elementary particle physics as the upper limit on the neutron EDM. So, even at the same sensitivity 10^{-24} e cm, as discussed in [7] for muons, the experiments with nuclei would compete with the best present EDM results. Certainly, progress in this direction well deserves serious efforts.

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