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BOUNDS ON ELECTRIC DIPOLE MOMENTS AND T-VIOLATING WEAK INTERACTIONS OF THE NUCLEONS

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A b s t r a c t

Using the limit on an electric dipole moment (edm) of the ^{129}Xe atom [1] the bounds on constants of T-odd electron-nucleon interaction ($< 4\cdot 10^{-6}\, G_F$) and nucleon-nucleon interaction ($< G_F$) as well as on edm of a proton ($|d_p| \leq 4\cdot 10^{-21}\, e\cdot cm$) and a neutron ($|d_n| \leq 1\cdot 10^{-21}\, e\cdot cm$) are obtained.

Although the CP-invariance violation was discovered many years ago[2] the decays of neutral K -mesons still remain the only physical phenomena where this effect was observed. This explains a great interest to the search for the electric dipole moment (edm) of elementary particles and atomic systems, one more possible manifestation of the T - and CP-invariance violation. The bounds obtained (see e.g. [3,4]) have reduced drastically the class of possible models of the T-violation.

The edm of the ^{129}Xe atom has been measured recently with a very small statistical error[1]:

$$d(^{129}Xe) = (-0.3 \pm 1.1) \cdot 10^{-26} \ e.cm \tag{1}$$

e is a proton charge. As it is shown below this result leads to a lot of knew bounds on parameters of T-odd interaction.

To begin with we consider the electron-nucleon tensor-pseudotensor interaction

$$\frac{i C_T G_F}{\sqrt{2}} \bar{\Psi}_N \gamma_5 \sigma_{\mu\nu} \Psi_N \bar{\Psi}_e \sigma^{\mu\nu} \Psi_e \tag{2}$$

where Ψ_N and Ψ_e are the nucleon and electron spinors, G_F is the Fermi constant, C_T is a parameter measuring the strength of this interaction. At the limit of an infinitely heavy nucleon the interaction (2) leads to the following Hamiltonian of an electron-nucleus interaction(see e.g.[5]):

$$H_T = 2i \frac{G_F}{\sqrt{2}} \rho(\vec{r}) \Sigma \frac{\vec{I}\vec{\gamma}}{I}$$

$$\vec{\Sigma} = \Sigma \frac{\vec{I}}{I} \equiv C_{Tn} \langle \vec{\sigma}_n \rangle + C_{Tp} \langle \vec{\sigma}_p \rangle \tag{3}$$

where I is the nuclear spin, $\vec{\sigma} = 2\vec{S}$, $\langle \vec{S}_p \rangle$ and $\langle \vec{S}_n \rangle$ are average spins of protons and neutrons in a nucleus , $\rho(\vec{r})$ is normalized density of spin-bearing nucleons $\int \rho \, dV = 1$. The result of a calculation of the atomic edm depends very slightly on the concrete choice of $\rho(r)$ (see [6]). We take

$\rho(r)$ coinciding with the charge density.

The $\langle\vec{\sigma}_n\rangle$ and $\langle\vec{\sigma}_p\rangle$ values for ^{129}Xe one can estimate as follows. In the frame of a shell model the ^{129}Xe nuclear spin is due to an unpaired neutron in the $3S_{1/2}$ -state, i.e. $\langle\vec{\sigma}_n\rangle = \vec{I}/I$. However, the value of magnetic moment of ^{129}Xe ($\mu = \mu_n$ = -1.91 nuclear magneton) produced in this way considerably differs from the experimental one $\mu(^{129}Xe)$ = = -0.77. The possible explanation can be connected with the fact that the magnetic moment is rather sensitive to admixture of proton configurations with an unpaired spin because the proton magnetic moment is large (μ_p = 2.79) and of the other sign than the neutron one. This circumstance makes it possible to evaluate $\langle\vec{\sigma}_p\rangle$. The difference between nuclear and neutron magnetic moments can be written as follows:

$$\mu - \mu_n = 2\mu_n\langle S_{nz}+S_{pz}-\tfrac{1}{2}\rangle + 2(\mu_p+|\mu_n|)\langle S_{pz}\rangle + \langle \ell_{pz}\rangle \qquad (4)$$

$$S_{pz}+S_{nz}+\ell_{pz}+\ell_{nz} = I_z = \frac{1}{2}.$$

If we neglect the contribution of spin-orbit interaction into the mixing of configuration then $S_{nz}+S_{pz}=\frac{1}{2}$, $\vec{L}=\vec{\ell}_n+\vec{\ell}_p=0$ and $\langle\vec{\ell}_p\rangle \sim \langle\vec{L}\rangle = 0$. Therefore from eq. (4) we find

$$^{129}Xe: \quad \langle\sigma_{pz}\rangle = \frac{1}{4}, \quad \langle\sigma_{nz}\rangle = \frac{3}{4} \qquad (5)$$

Let us pay attention to the large coefficient before $\langle S_{pz}\rangle$ in eq. (4) ($2(\mu_p+|\mu_n|)=9.4$). Probably it means that the accuracy of the definition of $\langle\sigma_{pz}\rangle$ is not bad. It is interesting that for ^{203}Tl and ^{205}Tl where in a $3S_{1/2}$ state there is an unpaired proton the analogous consideration leads to a quite similar result [7] :

$$^{203,205}Tl: \quad \langle\sigma_{nz}\rangle = \frac{1}{4}, \quad \langle\sigma_{pz}\rangle = \frac{3}{4} \qquad (6)$$

The interaction (3) leads to the mixing of atomic states of opposite parity and induces an edm of the atom. The calculation of the atomic edm was carried out with the aid of relativistic Hartree-Fock method. The interaction H_T is taken

into account in one-particle electron orbitals ($\psi \to \psi+\delta\psi$, $(H-E)\delta\psi = -H_T\psi$; see calculations of spatial parity violation in Ref. [6]).

For the estimation of calculation accuracy we find out the xenon polarizability by means of the analogous method (in this case $(H-E)\delta\psi = +e\vec{z}\psi$). The calculated value $\alpha = 26.9\, a_B^3$ proves to be surprisingly close to the experimental value $\alpha(Xe) \approx 27\, a_B^3$ which was obtained by means of a xenon refraction index [8] with the photon frequency correction.

The calculation of the xenon edm induced by interaction (3) gives:

$$d(^{129}Xe) = 0.41\cdot 10^{-20}\, e\cdot cm\, \Sigma \qquad (7)$$

$$\Sigma = \frac{3}{4} C_{Tn} + \frac{1}{4} C_{Tp}$$

Comparing (7) with the experimental value (1) one obtaines

$$\frac{3}{4} C_{Tn} + \frac{1}{4} C_{Tp} = (-0.7 \pm 2.7)\cdot 10^{-6} \qquad (8)$$

This result disagrees with the limit $|C_T| < 10^{-6}$ obtained in Ref [1] with the use of Märtensson-Pendrill calculations which were as it seems carried out in the shell model of the nucleus. Earlier by means of the measurement of linear stark shift in TlF molecule the bounds $C_{Tp} = (6 \pm 9.)\cdot 10^{-6}$ were obtained [9]. With (6) taken into account it should be written down in the form

$$\frac{3}{4} C_{Tp} + \frac{1}{4} C_{Tn} = (6 \pm 9)\cdot 10^{-6} \qquad (9)$$

This bounds are weaker than (8) and correspond to another combination of constants.

An atomic edm can appear also due to usual electromagnetic interaction of electrons and T-odd nuclear multipoles. The simplest among them is a nuclear edm. However, when the neutral atom is considered as a system of point-like particles with Coulomb interaction its total dipole moment vanishes despite of the presence of a nuclear edm, by virtue of the well-known Schiff theorem [10]. Taking into account the finite size of the nucleus the following form of T-odd electrostatic interaction can be obtained (see e.g. [11, 5,12]):

$$H_d = -4\pi e \vec{Q} \vec{\nabla} \delta(\vec{r}) \tag{10}$$

The coefficient Q which we shall call Schiff moment can arises due to edm of a nucleon or due to T-odd nuclear forces. In eq. (10) we use the limit $R_N \to 0$ (R_N is a nuclear size). Effect of finite nuclear size is taken into account in Q only $(Q \sim R_N^2)$. Strictly speaking, for a relativistic electron the approximation $R_N \to 0$ cannot be applied because of wavefunction divergency at $r \to 0$. It can be removed by simple substitution $\delta(\vec{r}) \to \rho(\vec{r})$. The corrections arising for the more accurate calculations are small $(\sim \frac{Z^2\alpha^2}{2} \sim 0.1)$. The atomic edm induced by interaction (10) is

$$d^{(Q)}({}^{129}Xe) = 2.7 \cdot 10^{-18} \frac{Q}{e \cdot fm^3} \cdot e \cdot cm \tag{11}$$

Comparing (11) with experimental value (1) we find

$$Q = (-1 \pm 4) \cdot 10^{-9}\, e \cdot fm^3 \tag{12}$$

Consider at first the case of Q caused by nucleon edm. In the frame of the shell model for the $S_{\frac{1}{2}}$ -neutron we have got [11,5]

$$Q = \frac{d_n}{6} (\langle r^2 \rangle - \langle r_q^2 \rangle) \tag{13}$$

d_n is a neutron dipole moment, $\langle r_q^2 \rangle$ and $\langle r^2 \rangle$ are the mean squares of radii of nuclear charge distribution and of probability distribution for unpaired $S_{\frac{1}{2}}$ -neutron. Calculation with Saxon-Woods potential gives $\langle r^2 \rangle - \langle r_q^2 \rangle = 3.8\, fm^2$ Comparing (13) and (12) we find

$$|d_n| < 1 \cdot 10^{-21}\, e \cdot cm \tag{14}$$

This bound is significantly weaker than result of direct measurement of the neutron edm [4]: $|d_n| < 5 \cdot 10^{-25}$. Nevertheless,

even if $d_n = 0$, the Schiff moment can arise due to the proton edm. Using the estimation (5) of the average spin of protons in ${}^{129}Xe$ nucleus we obtain

$$Q \sim \frac{d_p}{8}\, fm^2$$
$$|d_p| \lesssim 4 \cdot 10^{-21}\, e \cdot cm \tag{15}$$

This bound coincides with the best bound derived from the TlF experiment [9]. As for reliability of deriving of d_p the atomic part of calculations is essentially simpler and more precise for ${}^{129}Xe$ than for TlF. The nuclear part of calculation for ${}^{129}Xe$ as well as for ${}^{205}Tl$ is actually only estimation of an order of magnitude because of uncertainty of value $\langle r^2 \rangle - \langle r_q^2 \rangle$ whose even sign is not known exactly. (Considering polarization effects in Tl $\langle r^2 \rangle - \langle r_q^2 \rangle = 2 \pm 4\, fm^2$ [13]) .

The Schiff moment may arise also due to T-odd interaction of an unpaired nucleon and a nuclear core

$$H_{Tp} = \eta \frac{G_F}{\sqrt{2}} \frac{A}{2m} \vec{\sigma} \vec{\nabla} \rho \tag{16}$$

A - an atomic number, m - proton mass, ρ - normalized nuclear density $(\int \rho\, dV = 1)$, η - dimensionless constant measuring interaction strength.

In the frame of the shell model the Schiff moment is proportional to a charge of unpaired nucleon and for Xe amounts to zero. However with polarization of the nuclear core taken into account, $Q(Xe)$ is not zero. Its value can be estimated starting with relations (5), (6) and a value of the Schiff moment of Tl [12]: $Q(Tl) = -2 \cdot 10^{-8}\, \eta \cdot e \cdot fm^3$. Considering Q is proportional to $A^{2/3}$ [12] and $\langle \sigma_p \rangle = \frac{1}{4}$ we have got

$$Q({}^{129}Xe) \sim 0.4 \cdot 10^{-8}\, \eta \cdot e \cdot fm^3 \tag{17}$$

$$d(Xe) \sim 1 \cdot 10^{-26}\, \eta \cdot e \cdot cm \tag{18}$$

The estimation (18) agrees with that of a paper [12] where the accurate atomic calculation was not carried out.

From the comparison with the experimental value (1) we derive

$$|\eta| \lesssim 1 \qquad (19)$$

This bound confirms a result $\eta = -0.4 \pm 0.6$ obtained in [12] basing on experimental data on TlF molecule [9] and on molecular calculations [14].

It should be noted that the bound on the T-odd nucleon--nucleus interaction constant η may happen to be no less worthy than the best one on the edm of elementary particles because, for example, in the popular model of CP-violation suggested by Kobayashi and Maskawa, the nuclear edm induced by interaction (16) exceeds by two orders of magnitude the nucleon one [12] (respectively, the Schiff moment (17) exceeds (13), (15)).

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ОГРАНИЧЕНИЯ НА ЭЛЕКТРИЧЕСКИЕ ДИПОЛЬНЫЕ МОМЕНТЫ И Т - НЕИНВАРИАНТНЫЕ СЛАБЫЕ ВЗАИМОДЕЙСТВИЯ НУКЛОНОВ

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