About possibility to measure an electric dipole moment (EDM) of nuclei in the range $10^{-27} \div 10^{-32}$ $e \cdot cm$ in experiments for search of time-reversal violating generation of magnetic and electric fields.

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The possibility to measure an electric dipole moment (EDM) of nuclei in the range $10^{-27} \div 10^{-32}$ $e \cdot cm$ in experiments for search of time-reversal violating generation of magnetic and electric fields is discussed.

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Violation of the time reversal invariance of nature laws provides for elementary particles (nuclei, atoms) the possibility to possess an additional quantum characteristic - the electric dipole moment (EDM) $\vec{d}$, which could exist along with other characteristics such as electric charge, magnetic dipole moment, electric and magnetic polarisabilities. Plenty of experiments set the limits for EDM of different particles, atoms and nuclei [1, 2, 3, 4, 5, 6]. The attained experimental level gives, for example, for an electron EDM $d_e < 1.6 \cdot 10^{-27}$ $e \cdot cm$ [4]. The similar evaluations are provided for nuclei. Meanwhile, combine with calculations the experimental limits for d can be interpreted in terms of fundamental parity and time-invariance-violating (P-,T-odd) parameters. These limits tightly constrain competing theories of CP-violation.

So, it is very important to consider new possibilities for measuring constants describing T and CP-odd interactions [1, 7, 8, 9]. Very sensitive solid state based electron EDM experiments are preparing now [1]. They will provide for electron EDM measurement the sesitivity of about 10^{-32} $e \cdot cm$ or even better (10^{-35} $e \cdot cm$) [1].

The idea of the experiment is based on the measurement of a magnetic field, which appears since the electron spin (and, therefore, the magnetic moment) is oriented along an external electric field E due to interaction of electron EDM with the field E [5, 6].

According to [1] measurement of electron EDM at the sensitivity rate of about 10^{-32} $e \cdot cm$ requires substance cooling up to $T \sim 10^{-2}$ K, while for 10^{-35} $e \cdot cm$ the temperature $T \sim 10 \mu K$ is necessary.

But it was shown in [8] that for temperature values $T \approx 10^{-1} \div 10^{-2}$ the magnetic susceptibility of matter χ becomes compartible with 1 and higher. The energy of interaction of two electron magnetic dipoles for neighbour atoms occurs of order of $k_B T$ and greater (k_B is Boltzmann's constant). Thus, in this case, the collective effects, well-known in the theory of phase transitions in magnetism, should be taken into account while considering magnetization by an electric field. Particularly, spontaneous magnetization of a system can appear. Emergent great magnetic field is caused by fluctuations of a magnetic field and weak residual magnetic fields rather than external electric fields. In such conditions an electric field would not affect distinctly on the value of the measured magnetic field. Therefore, measurement of electron EDM in such conditions becomes difficult.

In the present paper it is shown that the above described problems make considerably attractive carrying out the experiment to search the EDM of nuclei by measurement of the magnetic (electric) field that appears at polarization of nuclear spins due to interaction of nuclear EDM with an external electric (magnetic) field. The magnetic moment of a nucleus is small. Therefore, considering the degree of polarization to be the same for electrons and nuclei we obtain the value of this magnetic field for nuclei of two or three orders lower then for electrons. But the phase transition of nuclear spins in an ordered state appears at temperatures $10^4 \div 10^5$ times lower comparing with electrons. According to [10] the nuclear dipole ordering appears at $T_N \sim 10^{-6}$ K. Let us consider the parameter $\varkappa = \frac{d_N E}{kT}$, which describes the degree of nuclei spin polarization due to interaction of the nuclear EDM d_N with an electric field E in the temperature range above the temperature of phase transition. The temperature T_N is $10^4 \div 10^5$ times lower than the similar temperature for electrons T_e ($T_e \sim 10^{-1} \div 10^{-2}$ K). Hence, for nuclei $\varkappa$ is $10^4 \div 10^5$ times greater than for electrons.

As a result, the magnetic field produced by nuclei cooled to the temperature T_N is even stronger than that produced by electrons cooled to the temperature T_e. As a consequence, the nuclear EDM can be measured with sensitivity about 10^{-32} $e \cdot cm$.

I. NUCLEI IN AN ELECTRIC FIELD AT LOW TEMPERATURES

Thus,let us consider a substance, placed into an electric field.

Interaction W_E of an EDM $\vec{d}_N$ of a nucleus with an electric field $\vec{E}$ is similar to interaction of magnetic moment of a nucleus with a magnetic field and can be expressed as:

$$W_E = -\vec{d}_N \vec{E} \tag{1}$$

where $\vec{d}_N = d_N \frac{\vec{J}}{J}$, $\vec{J}$ is the nucleus spin.

If the nucleus environment in the substance does not possess cubic symmetry, then the energy of interaction of nuclear quadrupole moment with a nonuniform electric field field produced nucleus environment should be added to (1). If an external magnetic field also presents, then the energy of interaction of nuclear magnetic moment with this field should be added to (1), too.

But here we will omit these contributions, assuming that there is no an external magnetic field and an elementary cell of the substance is cubic.

The interaction of nucleus with the field $\vec{E}$ (1) makes spins of nuclei at low temperature polarized similar to the polarization (magnetization) of nuclei by a magnetic field due to the interaction W_B of a nucleus magnetic moment μ_N with a magnetic field $\vec{B}$:

$$W_B = -\vec{\mu}_N \vec{B} \tag{2}$$

Spins of nuclei polarized by an electic field induce the magnetic field $\vec{B}_E$ and change in the magnetic flux Φ at the surface of a flat sheet of material (Fig.1):

$$\Delta\Phi_N = 4\pi\chi_N A \frac{d_N}{\mu_N} E^* \tag{3}$$

$$B_E = \frac{\Delta\Phi_N}{A} = 4\pi\chi_N \frac{d_N}{\mu_N} E^*, \tag{4}$$

where A is the sample area, χ_N is the magnetic susceptibility of nuclei subsystem. For the temperature range above the temperature of nuclear magnetic ordering the susceptibility χ_N is described by Langevin's formula as follows:

$$\chi_N \approx \frac{\rho\mu_N^2}{3k_B T}, \tag{5}$$

ρ is the number of nuclear spins in cm^3, k_B is Boltzmann's constant, $\mu_N = g_N\sqrt{J(J+1)}\mu_{NB}$, μ_{NB} is the nucleus Bohr magneton, g_N is the gyromagnetic ratio, E^* is the effective electric

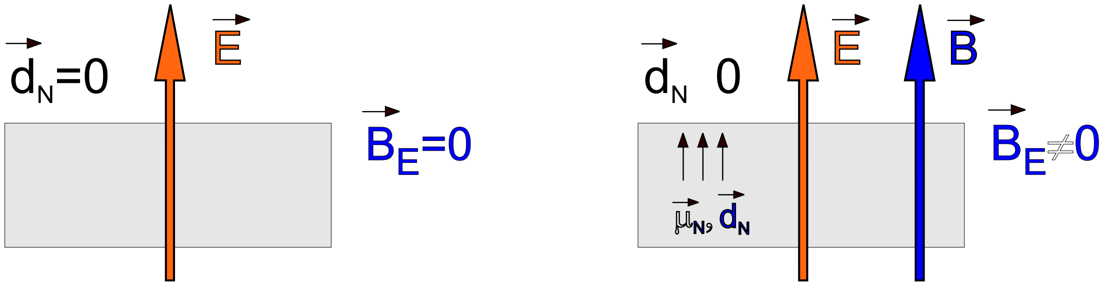

FIG. 1:

field at the location of the nuclear spin. Reasons providing interaction of an electric dipole moment with an electric field in spite of electrostatic shielding are specified in [1, 11].

Let us compare (4) for $\Delta\Phi_N$ with the similar expression in [1] for the magnetic flux $\Delta\Phi_e$ produced by electrons of atoms:

$$\Delta\Phi_e = 4\pi\chi_e A \frac{d_e}{\mu_a} E^*, \tag{6}$$

where χ_e is the magnetic susceptibility of a material caused by paramagnetic atoms, μ_a is the magnetic moment of the electron shell of the atom.

As it has been already mentioned, the magnitude of the susceptibility χ grows with temperature T tending to the temperature of magnetic ordering and appears equal to 1 at some temperature value T_1. At this temperature (note that for nuclei $T_{1N} \sim 10^{-6}$ K, while for atom spins $T_1 \sim 10^{-1} \div 10^{-2}$ K) the magnetic flux produced by nuclei is

$$\Delta\Phi_N(T_{1N}) = 4\pi A \frac{d_N {E^*}_N}{\mu_N}, \quad T_{1N} \sim 10^{-6}\ K, \tag{7}$$

the magnetic flux produced by atoms

$$\Delta\Phi_e(T_{1e}) = 4\pi A \frac{d_e {E^*}_a}{\mu_a}, \quad T_{1e} \sim 10^{-1} \div 10^{-2}\ K. \tag{8}$$

Let us consider temperature range close to the temperature of nuclear magnetic ordering. Suppose nuclear EDM is of the same order as EDM of an electron (atom) $d_N {E^*}_N \sim d_e {E^*}_a$.

Then, from (8,12) we obtain the magnetic flux $\Delta\Phi_N(T_{1N}) = \frac{\mu_a}{\mu_N}\Delta\Phi_e(T_{1e})$ i.e. the magnetic flux produced by nuclei is $\frac{\mu_a}{\mu_N}$ times greater than the magnetic flux produced by atom spins!

According to estimations [1] the sensitivity for atom EDM measurement $\sim 10^{-30}\ e \cdot cm$ in 10 days of averaging (and even $10^{-32}\ e \cdot cm$) can be obtained for the material temperature $T_a = 10^{-2}$ K.

Cooling of nuclear system to the temperature $T_N \approx 10^{-5}$ K provides the magnetic flux $\Delta\Phi_N = \frac{\mu_N}{\mu_a}\frac{T_a}{T_N}\Delta\Phi_e$. Due to $\frac{\mu_a}{\mu_N}\frac{T_a}{T_N} \approx 1$ the sensitivity for measurement of nuclear EDM appears the same as for electron (atom) EDM i.e. $d_N \approx 10^{-30} \div 10^{-32}\ e \cdot cm$.

Thus, the method for measurement of nuclear EDM by means of measurement of the induced magnetic field gives hope to obtain considerably substantial limit for the nuclear EDM. Let us note that in ferroelectric materials there are very intense internal electric fields $E*$ that are considerably more intense than external fields. This provides to advance to d_N values less than $10^{-32}\ e \cdot cm$.

II. NUCLEI IN A MAGNETIC FIELD AT LOW TEMPERATURES

If an external magnetic field acts on a material, the nuclei spins become polarized due to nucleus magnetization. Therefore, the nucleus electric dipole moments appears polarized, too. This results in the induction of an electric field $\vec{E}_B$ (Fig.2) (similar the electron case [1]):

$$E_B = 4\pi\rho d_N P(B), \tag{9}$$

where P represents the degree that the spins of nuclei are polarized in the sample.

There are methods providing $P(B) \sim 1$ for nuclei at low temperatures.

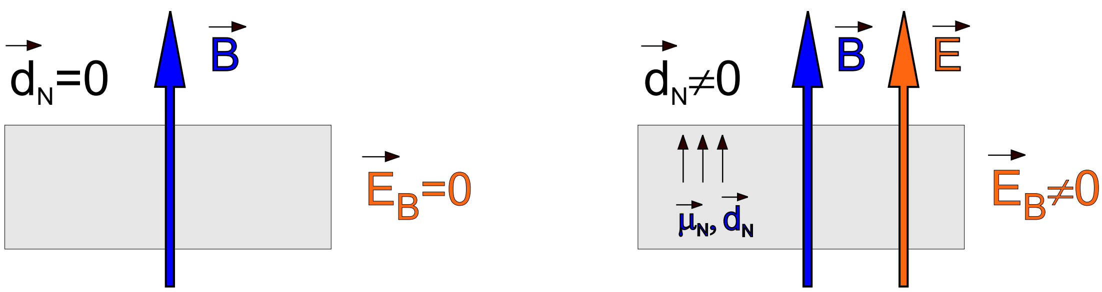

FIG. 2:

According to the analysis [1] the technique for electric fields measurement provides a sensitivity $\sim 10^{-30}\ e \cdot cm$ in 10 days of operation. The same sensitivity can be obtained for nuclear EDM due to high polarization degree available for nuclear spins at low temperatures.

An electric field induced by a magnetic field in vacuum can be increased by the use of electrostatic shielding or by selection of target shape (for example, a target having an edge). This gives hope for further improvement of the possibile limits for the EDM measurement ($d < 10^{-30}\ e \cdot cm$) in such experiments.

III. TIME-REVERSAL VIOLATING GENERATION OF STATIC MAGNETIC AND ELECTRIC FIELDS

It is important to pay attention that carrying out the proposed experiment to measure nuclear EDM one should consider additional effect of time-reversal violating generation of static magnetic and electric fields caused by the T-odd polarizability of atoms, molecules and other particles [7, 8, 9]. According to the idea of [7], an induced magnetic field appears on the particle due to the action of a field $\vec{E}$ under conditions of violation of P- and T-invariance (and similar, an induced electric field appears on the particle due to the action of a field $\vec{B}$). This new effect does not depend on temperature. An effect magnitude is determined by a P-odd T-odd tensor polarisability β_{ik}^T of a particle (atom, molecule, nucleus, neutron, electron and so on). For an atom (molecule), β_{ik}^T arises due to P- and T-odd interaction of electrons with a nucleus [7, 8, 9].

Let us place an atom (molecule) into an electric field $\vec{E}$. The induced magnetic dipole moment $\vec{\mu}(\vec{E})$ appears in this case [7]:

$$\mu_i(\vec{E}) = \beta_{ik}^T E_k, \tag{10}$$

The tensor β_{ik}^T (like any tensor of rank two) can be expanded into scalar, simmetric and antisimmetric parts.

The antisymmetric part of the tensor β_{ik}^T is proportional to $e_{ikl}J_l$, where e_{ikl} is the totally antisymmetric tensor of rank three. The symmetric part of the tensor β_{ik}^T is proportional to the tensor of quadrupolarization $Q_{ik} = \frac{3}{2J(2J-1)}[J_iJ_l + J_kJ_l - \frac{2}{3}J(J+1)\delta_{ik}]$. As a result

$$\beta_{ik}^T = \beta_s^T \delta_{ik} + \beta_v^T e_{ikl} J_l + \beta_t^T Q_{ik}, \tag{11}$$

where $\beta_s^T, \beta_v^T, \beta_t^T$ are the scalar, vector and tensor P-, T-odd polarizabilities of the particle, respectively. For a substance with the nonpolarized spins $Sp\ \rho(J)\vec{J} = 0$ and $Sp\ \rho(J)Q_{ik} = 0$ (here $\rho(J)$ is the atom (molecule) spin density matrix). As a result for such a substance, β_{ik}^T appears to be a scalar $\beta_{ik}^T = \delta_{ik}\beta_s^T$.

It follows from (8) that in a substance placed into electric field the magnetic field is induced [7]:

$$\vec{B}^{ind}(E) = 4\pi\rho\beta^T_{ik}\vec{E}^*_k, \tag{12}$$

where $\vec{E}^*_k$ is the local electric field acting on an atom in the substance.

Vice versa, if an atom (molecule, nucleus) is placed into a magnetic field, the induced electric dipole moment $\vec{d}(B)$ appears [7],

$$d_i(B) = \chi^T_{ik}B_k, \tag{13}$$

where the tensor polarizability χ^T_{ik} is $\chi^T_{ik} = \beta^T_{ki}$. The above dipole moment $\vec{d}(B)$ leads to the induction of an electric field in the substance:

$$E^{ind}_i(B) = 4\pi\rho\beta^T_{ki}\vec{B}^*_k, \tag{14}$$

where $\vec{B}^*$ is the local magnetic field, acting on the considered particle in the substance.

Polarized electron spins give one more contribution to the magnetic field

Therefore, the magnetic field $\vec{B}^*$, which is going to be measured in the proposed experiment, should be written as:

$$\vec{B}^* = \vec{B}^N_E + \vec{B}^{ind}(E) + \vec{B}^A_E, \tag{15}$$

where $\vec{B}^A_E$ is the magnetic field produced by atom spins.

Let us consider now the experiment to detect the electric dipole moment of the nucleus by means of measurement of the electric field (see (5)). In this case we also should take into consideration the effect of electric field induction by the magnetic field (13) and the electric field E^A_B produced by polarized EDM of atoms.

Thus, the electric field measured in the proposed experiment is as follows (see (9),(10)):

$$\vec{E}_B = \vec{E}^N_B + \vec{E}^{ind}(B) + \vec{E}^A_B. \tag{16}$$

So, measurement of $\vec{B}_E$ and $\vec{E}_B$ provides knowledge about nuclear EDM, electron EDM and β^T_s. To distinguish these contributions one should consider the fact that studying B_E and E_B dependence on temperature allows one to evaluate different contributions from [8].

It should be emphasized that atom EDM does not contribute to the discussed phenomena if the substance is diamagnetic (atom spin is equal to zero or spin atoms are nonpolarized) [8].

If the substance consists of several types of atoms (nuclei), then their contribution to the induced field is expressed as a sum of contributions from different atoms:

$$\vec{B}_E = \sum_n \vec{E}_n^*, \vec{E}_B = \sum_n \vec{B}_n^*, \tag{17}$$

IV. ABOUT CONTRIBUTION OF ELECTROMAGNETIC INTERACTION TO THE ELECTRIC DIPOLE MOMENT OF NUCLEI

Analysis of experimental limits obtained for EDM of atoms and nuclei was done in [11, 12, 13]. The possible values for constants describing T-odd, P-odd interaction were found there on the basis of calculation Shiff EDM of nuclei [12, 13]. The structure of an electric field inside a nucleus was also analysed and it was shown that it leads to an additional contribution to nuclear EDM, which was called LDM [12]. The mentioned contributions to EDM are finally caused by interference of strong, T-,P-odd and electrostatic interactions. Attention should drawn to the fact that there is one more contribution to nuclear EDM different from those, considered in [12, 13]. This addition is caused by electromagnetic currents [8].

According to the above the induced magnetic moment $\overrightarrow{\mu}_E$ of a particle appears due to action of a field $\overrightarrow{E}$ under conditions of violation of P- and T-invarince (and similar, induced electric dipole moment $\overrightarrow{d}_B$ of a particle appears due to the action of a magnetic field $\overrightarrow{B}$):

$$\mu_i^E = \beta_{ik}^T E_k, \tag{18}$$

$$d_i^B = \beta_{ki}^T B_k, \tag{19}$$

where β_{ik}^T is the T-odd polarizability tensor of the particle (atom, nucleus, neutron, electron and so on).

As a result, the induced electric $\overrightarrow{E}_{ind}(\overrightarrow{r})$ and magnetic $\overrightarrow{B}_{ind}(\overrightarrow{r})$ fields appear in space. The magnetic moment of a nucleus (multipoles of high orders) interacts with the field $\overrightarrow{B}_{ind}(\overrightarrow{r})$. Particularly, interaction of the magnetic moment density $\overrightarrow{\mu}(\overrightarrow{r})$ of a particle with the field $\overrightarrow{B}_{ind}(\overrightarrow{r})$ can be expressed as:

$$W_{ind} = -\int \overrightarrow{\mu}(\overrightarrow{r})\overrightarrow{B}_{ind}(\overrightarrow{r})d^3 \tag{20}$$

As the field $\overrightarrow{B}_{ind}(\overrightarrow{r})$ is proportional to the electric field $\overrightarrow{E}$, then (20) can be rewritten

$$W_{ind} = \chi_{TN}\mu_N \frac{\overrightarrow{J}}{J}\overrightarrow{E}, \tag{21}$$

where constant χ_{TN} is the T-odd susceptibility of a nucleus, μ_N is the magnetic moment of the nucleus.

The susceptibility χ_{TN} can be evaluated as [7, 8]:

$$\chi_{TN} \sim \frac{\beta_{TN}}{a^3}, \tag{22}$$

where a is the typical radius of a nucleus.

As one can see (21) is similar to the interaction of an electric dipole moment $d_\mu = \mu_N \chi_{TN}$ with an electric field.

One more contribution to the nuclear EDM appears by the following way. The magnetic moment of a nucleus μ_N creates the magnetic field $B_N \sim \frac{8\pi}{3}\frac{\rho}{A}\mu_N$ inside the nucleus, here $\frac{\rho}{A}$ is the nucleus density per one nucleon. According to (19) this field induces an additional contribution to the EDM $d \sim \beta_T B_N$.

More rigorously the mentioned contributions to the EDM can be calculated by including electromagnetic interactions between nucleons in Hamiltonian along with strong and weak interactions and by considering of radiation corrections to the energy of interaction of a nucleus with an external field [8].

As a result the total energy of nucleus interaction with an external field can be written as follows:

$$W = -d\frac{\vec{J}}{J}\vec{E} - \chi_T \mu \frac{\vec{J}}{J}\vec{E} = -\frac{1}{J}(d + \chi_T \mu)\vec{J}\vec{E} = -\frac{1}{J}(d + d_\mu)\vec{J}\vec{E} = -D_N\frac{\vec{J}\vec{E}}{J}, \tag{23}$$

where d is the contribution to EDM considered in [12, 13], d_μ is the contribution to EDM due to magnetic field induced inside the nucleus (let us call it pseudo-dipole moment d_μ), $D_N = d + d_\mu$ is nucleus EDM.

Now, let us estimate possible values of the susceptibility χ_{TN} and pseudo-dipole moment d_μ (PDM).

An induced magnetic field $B_{ind} \sim \frac{\mu_{ind}}{a^3}$ (a is some typical radius of the density distribution, for a nucleus it could be the radius of the nucleus).

Interaction of the magnetic moment μ of a particle with the field B_{ind} can be estimated as $W_{ind} \approx \frac{\mu\mu_{ind}}{a^3}$. The induced magnetic moment

$$\mu_{ind} \sim \beta_T E \sim \frac{\langle d\rangle \langle \mu\rangle}{\Delta}\eta_T E, \tag{24}$$

where $\langle d\rangle$ is the transition matrix element of the operator of electric dipole moment, $\langle \mu\rangle$ is the transition matrix element of the operator of magnetic dipole moment, Δ is the typical distance between levels of opposite parity (for neutron it is about 1 GeV, for nuclei it is about hundreds keV ÷ MeV), η_T is the coefficient of mixing of the opposite parity states by T-,P-odd interaction, $\eta_T \approx \frac{V_{TP}}{\Delta}$, V_{TP} is the matrix element of T-,P-odd interaction between states of opposite parity.

Therefore,

$$W_{ind} \sim \frac{\mu\mu_{ind}}{a^3} \sim \mu\frac{\langle d\rangle\,\langle\mu\rangle}{a^3\Delta}\eta_T E = \mu\chi_T E, \tag{25}$$

$$\text{the susceptibility } \chi_T \sim \frac{\beta_T}{a^3} \sim \frac{\langle d\rangle\,\langle\mu\rangle}{a^3\Delta}\eta_T, \tag{26}$$

$$d_\mu = \mu\chi_T \sim \chi_T\lambda_c(\mathrm{cm}\cdot e). \tag{27}$$

From (27) the following estimation for an electromagnetic contribution $d_{\mu N}$ to nucleus EDM can be odtained.

Considering a "free" nucleus (without electron shell) we can obtain from (27) the following estimation for the addition $d_{\mu N}$ induced by magnetic interactions

$$d_{\mu N} = \mu_N\chi_{NT} \sim A\frac{V_{coul}}{\Delta}\frac{\lambda_c}{a}\eta_{NT}\ \lambda_c\ \ \mathrm{cm}\cdot e, \tag{28}$$

$a = a_0 A^{\frac{1}{3}}$ ($a_0 = 1.2\cdot 10^{-13}\ cm$) is the nucleus radius, A is the number of nucleons in the nucleus, for this estimation it is suposed that $d \sim ea$, $\mu \sim \frac{e\hbar}{mc} = e\lambda_c$, $\lambda_c = \frac{\hbar}{mc}$ is the Compton wavelength of the nucleon, $V_{coul} = \frac{e^2}{a}$.

Suppose that typical difference between levels is about several MeV we obtain for heavy nuclei

$$d_{\mu N} \sim 10^{-15}\eta_{NT}\ e\cdot cm, \tag{29}$$

This estimation is done in assumption that nucleons are unstructured. Considering also a T-odd polarizability β_N of nucleons we can see that an external electric field induces a nucleon magnetic moment $\mu_{N\ ind} = \beta_N^T E$ and this magnetic moment creates a magnetic field inside the nucleus

$$B_{N\ ind} \sim \frac{8\pi}{3}\rho\mu_{N\ ind} = \frac{8\pi}{3}\rho\beta_N^T E, \tag{30}$$

The interaction of the magnetic moment of the nucleus with this field contributes to nucleus EDM as follows:

$$d_{N\ \mu} \sim \frac{8\pi}{3}\rho\mu_{N\ ind} = \frac{8\pi}{3}\rho\beta_N^T E, \tag{31}$$

where ρ is the density of nucleons in the nucleus, for a nucleon $\beta_N^T \sim \frac{V_{coul}^N}{\Delta}\eta_T^N{\lambda_c}^3$. Suppose that for a nucleon $a \sim \lambda_c$, $\Delta \sim 1Gev$, $V_{coul}^N \sim \frac{e^2}{\lambda_c}$.

Therefore, the additional contribution to the dipole moment of a nucleus aroused from the T-odd polarizability of nucleons is:

$$d_{N\ \mu} \sim \frac{8\pi}{3}\rho{\lambda_c}^3\frac{V_{coul}^N}{\Delta}\eta_T^N \sim 10\lambda_c\rho{\lambda_c}^3\frac{V_{coul}^N}{\Delta}\eta_T^N \approx 10\rho{\lambda_c}^3 10^{-2}\lambda_c\eta_T^N(cm\cdot e), \tag{32}$$

for nuclei with $A > 20$ the density $\rho = 10^{38}$, i.e. $d_{N\ \mu} \approx 10^{-18}\eta_T^N(cm\cdot e)$

The addition $d_{N\ \mu}$ can be expressed by means of $d_{n\ \mu}$ of nucleon:

$$d_{N\ \mu} = \frac{8\pi}{3}\rho{\lambda_c}^3 d_{n\ \mu} \approx 10^{-2} d_{n\ \mu}, \tag{33}$$

The same conclusion can be done from the following reasoning. The magnetic moment of a nucleus μ_N creates inside the nucleus a magnetic field $B_{ind} \sim \frac{8\pi}{3}\frac{\rho}{A}\mu_N$, where $\frac{\rho}{A}$ is the nucleus density per one nucleon. The field B_{ind} induces an electric dipole moment of nucleon

$$d_{ind} = \beta_N^T B_{ind}, \tag{34}$$

Total induced EDM is $D_{ind} = Ad_{ind} = \frac{8\pi}{3}\rho\beta_N^T\mu = d_{N\ \mu}$

It should be mentioned that the spin structure of the nuclear interaction between nuclons is similar to the magnetic interaction. Due to this reason the spin of the nucleus acts on the other nucleons by dint of the average nuclear field, depending on the spin orientation (let us call this field a pseudo-magnetic nuclear field, similar to the field appearing in a polarized nuclear target). The action of this field (similar to the action of an ordinary magnetic field) induces the electric dipole moment of nucleons in the nucleus. This contribution is appreciably (two orders) greater than $d_{N\ \mu}$ due to big value of the pseudo-magnetic nuclear field, but it is quite difficult to evaluate this contribution.

Let us consider deuteron EDM. Deuteron EDM was calculated in [14]. According to [14] deuteron EDM arouses due to mixing of stationary states of a system "neutron+proton" (interacting one with each other by strong interaction) by the T-odd, P-odd interactions.

According to the above analysis there are some additions to the deuteron EDM caused by the electromagnetic interactions between proton and neutron and nucleon polarizabilities.

Considering only strong interactions we can find a wavefunction of P-state of a system of two nucleons using an approximation of zero radius of nuclear forces, because strong interactions are short-range [14]. But electromagnetic interactions makes the interaction between n and p far-ranging. Thus, taking electromagnetic interaction into account we must consider for P-state a correcton to the wavefunction, caused by this interaction.

A matrix element of the transition current for the n-p system can be expressed in conventional form:

$$\vec{j}_{NF}(\vec{r}) = \frac{ie\hbar}{2m}\left(\Psi_F \vec{\nabla}_r \Psi_N^* - \Psi_N^* \vec{\nabla}_r \Psi_F\right) - \frac{e^2}{mc}\Psi_N(\vec{r})\vec{A}(\vec{r})\Psi_F + \tag{35}$$
$$c\ rot\left[\Psi_N^*\left(\frac{1}{2}(\mu_p+\mu_n)(\vec{\sigma}_p+\vec{\sigma}_n)+\frac{1}{2}(\mu_n-\mu_p)(\vec{\sigma}_n-\vec{\sigma}_p)\right)\Psi_F\right].$$

the term proportional to $(\vec{\sigma}_n + \vec{\sigma}_p)$ describes transitions between triplet states, while the term including $(\vec{\sigma}_n - \vec{\sigma}_p)$ corresponds to the transitions between triplet and singlet states. Let us place deuteron into an external electric field. The Hamiltonian of the n-p system is expressed as:

$$H = H_0 + V_E + V_W, \tag{36}$$

where H_0 is the Hamiltonian of the np system considering both the strong and electromagnetic interactions between nucleons, $V_E = -\vec{d}\vec{E}$, $\vec{d} = \frac{e}{2}\vec{r}$ is the operator of the electric dipole moment of the n-p system. According to [**?**] the energy of T-odd interaction

$$V_W = -\frac{g\,g_1}{4\pi m_p}\vec{J}\vec{\nabla}\frac{e^{-m_\pi r}}{r} + \frac{3g\,g_0}{8\pi m_p}(\vec{\sigma}_n - \vec{\sigma}_p)\vec{\nabla}\frac{e^{-m_\pi r}}{r}, \tag{37}$$
$$J = \frac{1}{2}(\vec{\sigma}_n + \vec{\sigma}_p)$$

Calculating the current $\vec{j}$ we should take the wavefuncton $\Psi_{F(N)}$ considering contributions of the second order over $V_E + V_W$ interacton.

Considering only strong and weak interactions for the deuteron EDM [14] one should take into account the first term proportional to $(\vec{\sigma}_n + \vec{\sigma}_p)$. Consideration of electromagnetic interactions leads to the conclusion that the term proportional to $(\vec{\sigma}_n - \vec{\sigma}_p)$ also contributes to the deuteron EDM.

So, due to electromagnetic interaction the deuteron EDM is determined by both the constants $g\,g_1$ and $g\,g_0$. Considering estimation (31-33) we obtain for deuteron $d_{\mu D} \sim 10^{-16}\eta_{DT}$ cm·e.

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[1] S.K. Lamoreaux, LANL e-print arXive: nucl-ex/0109014v4 (2002).

[2] Cheng Chin, Veronique Leiber, Vladan Vuletic, Andrew J. Kerman, and Steven Chu Phys.Rev. A **63**, 033401 (2001).

[3] M.V. Romalis, W.C. Griffith, and E.N. Fortson, LANL e-print arXive: hep-ex/0012001v1 (2000).

[4] B.C. Regan, Eugene D. Commins, Cristian J. Schmidt and David DeMille, *Phys.Rev.Lett* **88**, n.071805-1 (2002).

[5] F.L. Shapiro, Sov. Phys. Usp. **11** (1968) 345.

[6] B.V. Vasil'ev and E.V. Kolycheva, Sov. Phys. JETP **47** (1978) 243.

[7] V.G. Baryshevsky LANL e-print arXive: hep-ph/9912270v2 (1999); hep-ph/9912438v3 (2000).

[8] V. G. Baryshevsky, LANL e-print arXive: hep-ph/0307291 (2003).

[9] V. G. Baryshevsky and D. N. Matsukevich, *Phys.Rev.* **A66** (2002) 062110 (LANL e-print arXive: hep-ph/0002040 (2000)).

[10] A.Abraham, M.Goldman, *Nuclear magnetism: order and disorder*, Clarendon Press, Oxford 1982.

[11] Khriplovich I.B. *Parity Nonconservation in Atomic Phenomena*, (London: Gordon and Breach, 1991).

[12] V.A. Dzuba, V.V.Flambaum, J.Ginges, M.G.Kozlov, Phys.Rev. A **66**, 012111 (2002).

[13] V. F. Dmitriev and R. A. Senkov, Phys. Rev. Lett. VOLUME 91, NUMBER 21 (2003).

[14] I.B.Khriplovich, R.V.Korkin, Nucl. Phys. A **665**, 365 (2000).