About possibility to search the electron EDM at the level $10^{-28} \div 10^{-30}$ e·cm and the constant of T-odd, P-odd scalar weak interaction of an electron with a nucleus at the level $10^{-5} \div 10^{-7}$ in the heavy atoms and ferroelectrics

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Abstract

The T-odd phenomenon of induction of the magnetic field by a static electric field provides to study the electron EDM and constants of T-odd, P-odd interaction of an electron with a nucleus. Measurement of this magnetic field for ferroelectric materials (like $PbTiO_3$) at the level $B \sim 3{\cdot}10^{-18}\, G$ allows to derive the electric dipole moment of an electron at the level $d_e \sim 10^{-30}\, e{\cdot}cm$ and the constant of T-odd scalar weak interaction of an electron with a nucleus at the level $k_1^{nuc} \sim 10^{-9}$. The atomic magnetometry makes possible to measure fields $\sim 10^{-13}\ G/\sqrt{Hz}$ now. This means that for 10 days operation one can expect to obtain B at the level

$$B \sim 10^{-16}\, G,$$

and, therefore, the limits for d_e in $PbTiO_3$ at the level

$$d_e \sim 10^{-28} \ \text{ and } \ k_1^{nuc} \sim 10^{-7}.$$

that makes the discussed method beneficial for measuring d_e and k_1^{nuc}.

1 INTRODUCTION

Study of time-reversal (T) symmetry violation (and CP (charge conjugation, parity) symmetry violation through the CPT-theorem) beyond the Standard model is of great importance for selecting the fundamental interactions theory. This is the reason for focusing efforts on the preparing and carrying out the dedicated experiments. The searches of the EDM of an electron (atom, molecule, nuclei) and T-odd weak interactions of electrons with nuclei [1]-[4] are the most attractive.

In [5, 6] it was shown that measurement of the T-violating polarizability β^T (CP violating polarizability β^{CP}) by the use of the phenomenon of the magnetic field generation by a static electric field (and generation of the electric field by a static magnetic field) could be a method for such a search. Low temperatures are not required for these measurements and this is the advantage of the above method.

2 What values of β^T could be measured in heavy atoms and what values for the electron EDM and the constants of T-,P-odd scalar weak interaction of an electron with a nucleon could be derived from this measurement

According to [5, 6] an external electric field acting on a nonpolarized atom (molecule, nucleus) induces its magnetic dipole moment $\vec{\mu}_E$:

$$\vec{\mu}(\vec{E}) = \beta_s^T \vec{E}, \tag{1}$$

where β_s^T is the T-odd scalar polarizability of an atom (molecule, nucleus).

It follows from (1) that in a substance placed into an electric field the magnetic field is induced [5, 6]:

$$\vec{B}_E^{ind} = f\rho\beta_s^T \vec{E}^*, \tag{2}$$

where ρ is the substance density (i.e. the number of atoms (molecules) per cm^3), $\vec{E}^*$ is the local field acting on an atom (molecule) in the substance. Parameter f describes dependence of the macroscopic magnetic field of the sample on the sample shape, for example:

$$\text{for a sphere: } f = \frac{8\pi}{3}, \text{ for a cylinder: } f = 4\pi.$$

If the substance consists of atoms of several types, then their contributions to the induced field can be expressed as a sum of contributions from different types of atoms:

$$\vec{B}_E = f\rho \sum_n c_n \beta_{ns}^T \vec{E}_n^*, \vec{E}_B = f\rho \sum_n c_n \beta_{ns}^T \vec{B}_n^*, \tag{3}$$

where c_n is the concentration of atoms of the type n, $\vec{E}_n^*$ and $\vec{B}_n^*$ are the local fields acting on atoms of the type n.

According to [5, 6] the magnitude of the polarizability β_s^T is determined by both the electron EDM d_e and T-odd scalar weak interaction of an electron with a nucleus, which is described by the constants k_1^p and k_1^n (k_1^p is the constant defining interaction with a proton, k_1^n is that for a neutron). It is known [7] that the expression for T-odd scalar weak interaction of an electron with a nucleus includes constants k_1^p and k_1^n as the sum $(Zk_1^p + Nk_1^n)$, where Z and N are the numbers of protons and neutrons in the nucleus, respectively. As a consequence, measurement of β_s^T provides for getting information about d_e and the above sum [5, 6].

Evaluations for d_e and the sum $(Zk_1^p + Nk_1^n)$ could be derived from β_s^T.

Pioneering calculations of these contributions to the polarizability β_s^T for rare gas atoms were done in [8]. It should be noted that in [8] contribution of T-odd scalar weak interaction was calculated as the function of the constant $k_1^{nuc} = \frac{1}{Z}(Zk_1^p + Nk_1^n) = k_1^p + \frac{N}{Z}k_1^n$.

Let us evaluate now the least values of β_s^T could be expected for measuring in the nearest future.

From (2) it can be obtained

$$\beta_s^T = \frac{B_E}{f\rho E^*} \tag{4}$$

According to [1] we can expect for magnetic induction measurement the sensitivity up to $\sim 3 \cdot 10^{-18} G$. Such sensitivity of magnetic induction measurement provides for polarizability β_s^T measurement the sensitivity:

$$\beta_s^T = \frac{3 \cdot 10^{-18}}{f\rho E^*}$$

Let us consider first a non-ferroelectric material, for example: liquid or solid Xe in the highest available external field, which does not exceed break-down voltage $E^* \sim 4 \cdot 10^5\ V/cm = \frac{4}{3} \cdot 10^3$ CGSE.

In this case (the density of liquid and solid components $\rho \approx 2 \cdot 10^{22}\ cm^{-3}$) β_s^T can be evaluated as follows

$$\beta_s^T \approx 10^{-44}\ cm^3.$$

Let us consider what limits for d_e and k_1^{nuc} could be got from β_s^T measurement at such level.

According to [8] contributions from d_e and k_1^{nuc} sharply depend on the nucleus charge Z (as Z^5). For example, from these calculations it follows that β^T for Rn ($Z = 86$) 20 times exceeds β^T for Xe ($Z = 54$) . In particular, according to [8] the contribution to the polarizability β_s^T caused by the electric dipole moment of electron for Xe atom ($Z = 54$) can be expressed in atomic units as follows:

$$\beta_{s\ Xe}^T = 1.5 \cdot 10^{-2}\ d_e \tag{5}$$

that can be rewritten in CGSE units as:

$$\beta_{s\ Xe}^T = 1.5 \cdot 10^{-2}\ d_e[e \cdot cm] a_A^2 = 1.5 \cdot 10^{-2}\ d_e[e \cdot cm](5 \cdot 10^{-9})^2, \tag{6}$$

where a_A is the atomic length unit.

Therefore, we obtain

$$d_e = \frac{\beta_{s\ Xe}^T}{3.75 \cdot 10^{-19}} \approx 2.7 \cdot 10^{-26} \tag{7}$$

(the similar evaluation $d_e \sim 6 \cdot 10^{-26}$ is cited in [8]).

At the same time for radon Rn ($Z = 80$) we can get from the Table 1 in [8]

$$\beta_{s\ Rn}^T = d_e[e \cdot cm] 2.5 \cdot 10^{-17} \tag{8}$$

i.e.

$$d_e = 4 \cdot 10^{-28} \tag{9}$$

and this result raises hopes when keeping in mind that the up-to-date limit for the electron EDM $d_e(Tl) < 1.6 \cdot 10^{-27}\ e \cdot cm$ [2].

However, Rn is nonstable and, therefore, it is not right for the experiments. Though there are no calculations for other types of atoms, the expectation to find the similar Z^5 dependence for other atoms (for example, for Pb ($Z = 82$) or U ($Z = 92$)) seems also valid, because the lack (or excess) of number of electrons ΔN_e with respect to such number in the closed shell is much less than the total number of electrons in a heavy atom. This is why the value of polarizability for Pb ($Z = 82$) could be supposed close to that for Rn (while for U it could be even greater).

Thus, such evaluation for Pb and U polarizabilities gives hope to get for the EDM measurement the limit $d_e \leq 4 \cdot 10^{-28}\ e \cdot cm$ (for the same external electric field $E \sim 4 \cdot 10^5\ \frac{V}{cm}$). As Pb and U are metals, then, for example, oxides should be used.

Let us consider now the limitations for the constant k_1^{nuc} of electron-nucleus T-odd scalar weak interaction those could be obtained from the above β^T evaluation.

According to the Table 1 in [8] the similar evaluations for Xe provide

$$\text{in atomic units } \beta_S^T = 5.3 \cdot 10^{-15}\ k_1$$

$$\text{in CGSE units } \beta_S^T = 5.3 \cdot 10^{-15}\ k_1^{nuc}(a_A)^3\ (a_A = 5 \cdot 10^{-9}\ cm)$$

Therefore,

$$k_1^{nuc} \approx 2 \cdot 10^{-5}$$

At the same time estimation for Rn gives

$$k_1^{nuc} \approx 3 \cdot 10^{-7}.$$

Now the experimentally obtained limit for Xe is $k_1^{nuc} \leq 10^{-4}$. The experiment, which is planned with Cs [3], could provide for $k_1^{nuc} \leq 5 \cdot 10^{-6}$ [6].

If again consider the evaluation made for Rn close to those could be obtained for Pb and U then the ten times reduction of limit for k_1^{nuc} measurement could be expected in the experiments with Pb and U oxides comparing with that is planned with Cs [3].

3 Possible limit for d_e and k_1^{nuc} could be obtained in the ferroelectric $PbTiO_3$

It is known that internal electric fields in ferroellectrics are very large. $PbTiO_3$ is a typical ferroelectric that has been considering as a candidate for use in the EDM searches. According to evaluations [9] the field acting on the Pb atom in $PbTiO_3$ can be estimated as $E \approx 10^8 \ \frac{V}{cm}$. This means that measuring the magnetic field induced by an external electric field acting on a $PbTiO_3$-sample one can expect to measure β_s^T at the level $\beta_s^T \sim 10^{-46}\ cm^3$ (that is two orders less than the above estimation $\beta_s^T \sim 10^{-44}$ cm^3). Therefore the limits for d_e and k_1^{nuc} measurement are

$$d_e \sim 10^{-30} e \cdot cm \text{ and } k_1^{nuc} \sim 10^{-9}.$$

4 Conclusion

Measurement of the magnetic field for ferroelectric materials (like $PbTiO_3$) at the level $B \sim 3 \cdot 10^{-18}$ G allows to measure β_s^T at the level $\beta_s^T \approx 10^{-46}\ cm^3$. This makes possible to derive the electric dipole moment of an electron at the level $d_e \sim 10^{-30}\ e \cdot cm$ and the constant of T-odd scalar weak interaction of an electron with a nucleus at the level $k_1^{nuc} \sim 10^{-9}$.

Considering that the up-to-date limits are $d_e(Te) \leq 10^{-27}\ e \cdot cm$ and $k_1^{nuc} \sim 10^{-4}$, the first step goal could be posed as d_e search at the level $10^{-28}\ e \cdot cm$ and, hence, reduce the requirements for B measurement to $B \sim 3 \cdot 10^{-16}\ G$. An attempt to measure $k_1^{nuc} \sim 10^{-5}$ result in easier requirement for B measurement $B \sim 3 \cdot 10^{-14}\ G$. According to [10] the atomic magnetometry makes possible to measure fields $\sim 10^{-13}\ G/\sqrt{Hz}$ now. This means that for 10 days operation one can expect to obtain B at the level

$$B \sim 10^{-16}\ G,$$

and, therefore, the limits for d_e in $PbTiO_3$ at the level

$$d_e \sim 10^{-28} \text{ and } k_1^{nuc} \sim 10^{-7}.$$

The above reasoning makes the proposed method beneficial for measuring d_e and k_1^{nuc}.

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