

Time-Reversal-Violating Generation of Static Magnetic and Electric Fields and a Problem of Electric Dipole Moment Measurement

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It is shown that in the experiments for the search of the electric dipole moment of an electron (atom, molecule) the T -odd magnetic moment induced by an electric field and the T -odd electric dipole moment induced by a magnetic field will be also measured. How to distinguish these contributions is discussed here.

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Nowadays there is appreciable progress in the development of methods for the measurement of ultraweak magnetic and electric fields. Therefore, new experiments for the measurement of the electric dipole moment (EDM) d of an electron [1] are being prepared. The EDM of a particle exists if parity (P) and time-reversal (T) invariance are violated. Investigation of the EDM existence could provide knowledge about physics beyond the standard model [1–4]. Shapiro's idea [5] to measure the electron EDM by applying a strong electric field to a substance that has unpaired electron spins is being used for the EDM search [1,6]. The interaction W_E of the electron electric dipole moment \vec{d} with an electric field \vec{E} depends on their orientations:

$$W_E = -\vec{d}\vec{E}, \quad (1)$$

where $\vec{d} = d\vec{J}$, \vec{J} is the atom spin and d is the EDM.

Spins of electrons (atoms) at low temperature appear to be polarized due to (1) similar to the polarization (magnetization) of electrons by a magnetic field in paramagnetic substances due to the interaction W_B of an electron (atom) magnetic moment $\vec{\mu}$ with a magnetic field \vec{B} ,

$$W_B = -\vec{\mu}\vec{B}. \quad (2)$$

Spins of electrons (atoms) polarized by an electric field induce the magnetic field \vec{B}_E and change in the magnetic flux Φ at the surface of a flat sheet of material [1]:

$$\Delta\Phi = 4\pi\chi A dE^*/\mu_a, \quad (3)$$

$$B_E = \frac{\Delta\Phi}{A} = 4\pi\chi \frac{d}{\mu_a} E^*, \quad (4)$$

where χ is the magnetic susceptibility, $\chi \approx \frac{\rho\mu_a^2}{3k_B T}$, ρ is the number density of spins of interest, k_B is Boltzmann's constant, and T is the sample temperature. In the cases where simple Langevin paramagnetism is applicable, E^* is the effective electric field at the location of the spins, $\mu_a = g\sqrt{J(J+1)}\mu_B$, where μ_B is the Bohr magneton, μ_a is the atomic or ionic magnetic moment, g is the Lande factor, and A is the sample area.

If an external magnetic field acts on either a paramagnetic or a ferromagnetic material, the spins in the substance become polarized due to substance magnetization.

Therefore, the electric dipole moments appear polarized, too. This results in the induction of an electric field \vec{E}_B (see the DeMille reference in [1]):

$$E_B = 4\pi\rho dP(B), \quad (5)$$

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

According to the analysis [1], modern methods for the measurement of B_E and E_B provide sensitivity for electric dipole moment measurement of about $10^{-32}e$ cm and, in some cases, even $10^{-35}e$ cm.

It is important to pay attention to another mechanism of time-reversal violating generation of magnetic and electric fields that has been discussed in [7]. According to the idea of [7], an induced magnetic moment $\vec{\mu}(\vec{E})$ of a particle appears due to the action of a field \vec{E} under conditions of violation of P and T invariance (and similarly, an induced electric dipole moment \vec{d}_B of a particle appears due to the action of a field \vec{B}). This new effect does not depend on the temperature. An effect magnitude is determined by a P - and T -odd tensor polarizability β_{ik}^T of a particle (atom, molecule, nucleus, neutron, electron, and so on). An atom (molecule) β_{ik}^T arises due to P - and T -odd interaction of electrons with a nucleus. For the stationary state of an atom (molecule) $|N_0\rangle$ the tensor β_{ik}^T is as follows:

$$\beta_{ik}^T = \sum_F \frac{\langle N_0|\hat{d}_i|F\rangle\langle F|\hat{\mu}_k|N_0\rangle + \langle N_0|\hat{\mu}_i|F\rangle\langle F|\hat{d}_k|N_0\rangle}{E_F - E_{N_0}}, \quad (6)$$

where $|F\rangle$ is the wave function of a stationary state of the atom, considering T -odd interaction V_w^T , E_F , and E_{N_0} are the energies of the atom (molecule) stationary states, \vec{d} and $\vec{\mu}$ are the operators of the electric dipole moment and the magnetic moment, respectively, and $i, k = 1, 2, 3$ correspond to the axes x, y, z .

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

$$\mu_i(\vec{E}) = \beta_{ik}^T E_k. \quad (7)$$

The tensor β_{ik}^T (like any tensor of rank two) can be

expanded into scalar, symmetric, and antisymmetric 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

$$\beta_{ik}^T = \beta_s^T \delta_{ik} + \beta_v^T e_{ikl}J_l + \beta_t^T Q_{ik}, \quad (8)$$

where β_s^T , β_v^T , β_t^T are the scalar, vector, and tensor P - and T -odd polarizabilities of the particle, respectively. For a substance with the nonpolarized spins $S\rho\rho(J)\vec{J} = 0$ and $S\rho\rho(J)Q_{ik} = 0$ [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 $\beta_{ik}^T = \delta_{ik}\beta_s^T$.

Placement of a nonpolarized atom (molecule or nucleus) into an electric field induces the magnetic dipole moment $\vec{\mu}_E$:

$$\vec{\mu}(\vec{E}) = \beta_s^T \vec{E}, \quad (9)$$

where $\beta_s^T = \sum_F \frac{\langle N_0 | \hat{d}_z | F \rangle \langle F | \hat{\mu}_z | N_0 \rangle + \langle N_0 | \hat{\mu}_z | F \rangle \langle F | \hat{d}_z | N_0 \rangle}{E_F - E_{N_0}}$, \hat{d}_z and $\hat{\mu}_z$ are the z components of the operators of the electric dipole moment and magnetic moment, respectively, and axis z is parallel to the electric field \vec{E} . It should be emphasized that for strong fields [when the distance between atom (molecule) levels is comparable with the energy of interaction with an electric \vec{E} (magnetic \vec{B}) field] β_s^T depends on \vec{E} (\vec{B}). Weak interaction is much weaker than strong and electromagnetic interactions. Therefore, to find the wave function $|F\rangle$, the perturbation theory can be applied:

$$|F\rangle = |f\rangle + \sum_n \frac{\langle n | V_w^T | f \rangle}{E_f - E_n} |n\rangle = |f\rangle + \sum_n \eta_{nf}^T |n\rangle, \quad (10)$$

where $|f\rangle$ is the wave function of an atom in the absence of weak interactions and the mixing ratio is $\eta_{nf}^T = \frac{\langle n | V_w^T | f \rangle}{E_f - E_n}$. It should be mentioned that for theoretical analysis of β_s^T in a substance it is necessary to find the wave function of an excited state of an atom in the substance, which is difficult to do.

It follows from (9) that in a substance placed into an electric field, the magnetic field is induced [7]:

$$\vec{B}_E^{\text{ind}} = 4\pi\rho\beta_s^T \vec{E}^*. \quad (11)$$

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

$$d_i(B) = \chi_{ik}^T B_k, \quad (12)$$

where the tensor polarizability χ_{ik}^T is $\chi_{ik}^T = \beta_{ki}^T$. The dipole moment $\vec{d}(B)$ leads to the induction of an electric field in a substance: $E_i^{\text{ind}}(B) = 4\pi\rho\beta_{ki}^T \vec{B}_k^*$, where \vec{B}^* is the local magnetic field, acting on the considered particle in the substance.

If an atom is found in a point with cubic symmetry (or in a liquid), then $\langle Q_{ik} \rangle = S\rho\rho(J)Q_{ik} = 0$ and $\langle \vec{J} \rangle = S\rho\rho(J)\vec{J} \parallel \vec{B}^*$. As a result, the terms including β_v^T and β_t^T turn to zero ($e_{ikl}\langle J_l \rangle B_k^* = e_{ikl}B_l^* B_k^* = 0$).

As a consequence, in this case

$$E_{\text{ind}}(B) = 4\pi\rho\beta_s^T \vec{B}^*. \quad (13)$$

Hence, analyzing the results of the experiment proposed in [1], one should consider that the appearance of the induced magnetic and electric fields is caused by the following: (i) A magnetic field is induced due to the interaction of the electric dipole moment of an atom with an external electric field [1,5] [see (3) and (4)]. (ii) A magnetic field is induced due to the mechanism [7] [see (11)]. (iii) A magnetic field appears as a result of polarization (magnetization) of atom magnetic moments by the local induced magnetic field \vec{B}_{loc} , due to the interaction W of the magnetic dipole moment of an atom with this field

$$W = -\vec{\mu}_a \vec{B}_{\text{loc}}. \quad (14)$$

The local field \vec{B}_{loc} is the sum of two contributions:

$$\vec{B}_{\text{loc}} = \vec{B}_{E\text{loc}} + \vec{B}_{\text{loc}}^{\text{ind}}, \quad (15)$$

where the field $\vec{B}_{E\text{loc}}$ is the local magnetic field acting on an atom from the polarized [by mechanism [1,5], see (3) and (4)] magnetic moments of the other atoms of the sample. This field depends on temperature and its contribution could be neglected for those temperature values, which provide $\chi \ll 1$. But for temperature $T < 1$ K the susceptibility $\chi \sim \frac{1}{T}$ becomes comparable with 1 and higher, and for neighbor atoms the energy of interaction of two magnetic dipoles occurs in the order of $k_B T$ and greater. Thus, in this case, the collective effects, well-known in the theory of phase transition in magnetism, should be taken into account while considering magnetization by an electric field.

The field $\vec{B}_{\text{loc}}^{\text{ind}} = \vec{B}_{1\text{loc}}^{\text{ind}} + \vec{B}_{2\text{loc}}^{\text{ind}}$ does not depend on temperature.

The field $\vec{B}_{1\text{loc}}^{\text{ind}} = \chi_{1\text{loc}}^T \vec{E}^*$ is the local magnetic field produced in the point of the considered atom location by the magnetic moments of atoms of the substance (except for the considered atom) induced by the aid of mechanism [7] [see (6) and (8)]; $\chi_{1\text{loc}}^T \sim \rho\beta_s^T$ is the local P - and T -odd susceptibility of the substance. In general case, $\chi_{1\text{loc}}^T$ is a tensor, but if the atom surrounding possesses cubic symmetry, then the principal contribution to this tensor is made by its scalar part ($\chi_{1\text{loc}}^T$ depends on the substance density and sample shape: for a sphere $\chi_{1\text{loc}}^T = \frac{8\pi}{3}\rho\beta_s^T$; for a cylinder $\chi_{1\text{loc}}^T = 4\pi\rho\beta_s^T$).

The field $\vec{B}_{2\text{loc}}^{\text{ind}}$ is the self-induced magnetic field of the considered atom. The magnetic moment (T -odd current) of the atom induced by an electric field acting on the atom due to mechanism [7,8] causes the appearance of the magnetic field inside the atom:

$$\vec{H}_E^T(\vec{r}) = \text{rot} \vec{A}_E^T(\vec{r}), \quad (16)$$

where the vector potential $\vec{A}_E^T(\vec{r}) = \frac{1}{c} \int \frac{j_E^T(\vec{r}')}{|\vec{r}-\vec{r}'|} d^3r'$, $j_E^T(\vec{r}')$ is the T -odd part of the transition current density operator for an atom (molecule) placed in an electric field [it is calculated by the use of the wave functions (10)]. The Hamiltonian of magnetic interaction of an atom with the field \vec{A}_E^T can be expressed as [8]

$$W_{2\text{loc}} = -\frac{1}{2c} \int [\vec{j}(\vec{r})\vec{A}^T(\vec{r}) + \vec{A}^T(\vec{r})\vec{j}(\vec{r})] d^3r, \quad (17)$$

where $\vec{j}(\vec{r})$ is the atom transition current density operator calculated with the atom wave function without consideration of P - and T -odd interactions, $\vec{j}(\vec{r}) = \text{crot}\vec{\mu}(\vec{r})$, and $\vec{\mu}(\vec{r})$ is the operator of the atom magnetic moment density. If the atom is found in a point with the cubic symmetry (or in a liquid) then we may omit contributions from atom multipoles.

In this case the above expression can be written as

$$W_{2\text{loc}} = -\vec{\mu}_a \vec{B}_{\text{ind}} = -\chi_a^T \vec{\mu}_a \vec{E}_{\text{loc}}^*, \quad (18)$$

where $\vec{\mu}_a = \mu_a \vec{j}$ and χ_{at}^T is the T -odd atom susceptibility that does not depend on the substance density and the sample shape, $\chi_{\text{at}}^T \sim \beta_s^T \frac{1}{a^3}$ (here a is the typical radius of distribution density of the magnetic moment induced by the electric field in the atom [7]).

As a result one can obtain

$$\vec{B}_{\text{loc}}^{\text{ind}} = (\chi_{1\text{loc}}^T + \chi_{\text{at}}^T) \vec{E}_{\text{loc}}^* = \chi_{\text{loc(subst)}}^T \vec{E}_{\text{loc}}^*, \quad (19)$$

$$\chi_{\text{loc(subst)}}^T = \chi_{1\text{loc}}^T + \chi_{\text{at}}^T. \quad (20)$$

The interaction (2) of the magnetic moment of an atom with the induced magnetic field causes the appearance of the magnetic field due to different populations of magnetic levels of the atom in the field \vec{B}_{loc} in thermal equilibrium

$$\vec{B}_{\text{ind}}' = 4\pi\chi \vec{B}_{\text{loc}} \approx 4\pi\chi \vec{B}_{\text{loc}}^{\text{ind}} = 4\pi \frac{\rho \mu_a^2}{3k_B T} \chi_{\text{loc(subst)}}^T \vec{E}_{\text{loc}}^*, \quad (21)$$

the field $\vec{B}_{\text{loc}} = \vec{B}_{E\text{loc}} + \vec{B}_{\text{loc}}^{\text{ind}}$, but for those temperature values that provide $\chi \ll 1$, $\vec{B}_{E\text{loc}}$ contribution can be neglected and it is omitted here.

Therefore, the flux $\Delta\Phi$ that is going to be measured in the experiment proposed in [1] should be written as

$$\begin{aligned} \Delta\Phi &= AB_E \\ &= 4\pi A \left(\chi \frac{d}{\mu_a} + \rho \beta_s^T + \chi \chi_{\text{loc(subst)}}^T \right) E^* \\ &= 4\pi A \left[\chi \left(\frac{d + \mu_a \chi_{\text{at}}^T}{\mu_a} + \chi_{1\text{loc}}^T \right) + \rho \beta_s^T \right] E^*, \quad (22) \end{aligned}$$

$$\vec{B}_E = 4\pi \left[\chi \left(\frac{d + \mu_a \chi_{\text{at}}^T}{\mu_a} + \chi_{1\text{loc}}^T \right) + \rho \beta_s^T \right] E^*, \quad (23)$$

where $\chi = \frac{\rho \mu_a^2}{3k_B T}$.

It should be noted that the quantity $d + \mu_a \chi_{\text{at}}^T$ is the electric dipole moment of an atom available for measurement in conventional EDM experiments studying atom (molecule) spin precession in an external electric field. It is well-known that the atom EDM has arisen from several mechanisms: the contribution proportional to d_e and the contribution due to T - and P -odd interaction of atom electrons with nuclear nucleons (dependent and independent on nuclear spin) [9].

According to (18) and (23), there is one more addition to the EDM $\sim \mu_a \chi_{\text{at}}^T$.

Note that the contribution to the atom EDM proportional to the nucleus spin I is equal to zero if the sample temperature is high ($\langle I \rangle = 0$ at high temperatures).

Let us consider now the experiment to detect the electric dipole moment of the electron by means of measurement of the electric field [1] [see (5)]. In this case we also should take into consideration the effect [7] of the EDM induction by the magnetic field (12).

Thus, the electric field measured in the experiment [1] is as follows [see (9) and (10)]:

$$E_B = 4\pi\rho [d_a P(B) + \beta_s^T B^*]. \quad (24)$$

Here d_a is the atom EDM containing contribution $\sim \beta_s^T \frac{\mu_a}{a^3}$ induced according to (12) by the magnetic field $\sim \frac{\mu_a}{a^3}$ that is produced inside the paramagnetic atom by its electrons.

So, measurement of $\Delta\Phi$ and E_B provides knowledge about the atom EDM and β_s^T . To distinguish these contributions one should consider the fact that χ and $P(B)$ depend on temperature, while β_s^T does not. Therefore, studying B_E and E_B dependence on temperature allows one to evaluate contributions from the EDM and β_s^T to the measured effect.

It should be particularly emphasized that $\Delta\Phi$ and E_B differ from zero even when the electron EDM d_e is equal to zero.

It should be also emphasized that the polarizability β_s^T differs from zero even for atoms with the zero spin, for that the EDM is absent. In this case (as well as for high temperatures when the average atom spin $\langle \vec{J} \rangle = 0$) only the effect [7], described by the terms (23) and (24), proportional to β_s^T , contributes to the induced electric and magnetic fields. If the substance consists of several types of atoms, then the induced field is expressed as a sum of contributions from different atoms:

$$\vec{B}_E = 4\pi\rho \sum_n c_n \beta_{ns}^T \vec{E}_n^*, \quad \vec{E}_B = 4\pi\rho \sum_n c_n \beta_{ns}^T \vec{B}_n^*, \quad (25)$$

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

Now let us consider what information about constants of T - and P -odd interaction of an electron with a nucleus can be obtained from studying the effect [7] of time-reversal violating generation of fields \vec{E}_B and \vec{B}_E [described by (25)].

According to [1] we can expect the magnetic induction sensitivity to be about $3 \times 10^{-15} G/\sqrt{\text{Hz}}$. In ten days of averaging the sensitivity is $\sim 10^{-18}$ G. This leads to the sensitivity for d_e measurement of about $10^{-32} e \text{ cm}$ [1].

Such sensitivity of magnetic induction measurement provides for polarizability β_s^T measurement of the sensitivity $\beta_s^T = \frac{B_E}{4\pi\rho E} \sim 10^{-43} \text{ cm}^3$ (it is supposed that $\rho \approx 2-3 \times 10^{22}$ and $E^* \sim 10 \frac{\text{kV}}{\text{cm}}$, for example, for liquid and solid Xe $\rho \approx 2 \times 10^{22}$).

Let us consider now the possibilities given by the experiment studying the electric field that is induced by a magnetic field for measurement of the polarizability β_s^T [7]. Analysis [1] shows that existing methods of the electric field measurement allow one to measure electric fields $E \sim 10^{-13}-10^{-14} \frac{\text{V}}{\text{cm}} \sim 3 \times 10^{-16}-3 \times 10^{-17}$ CGS (centimeter-gram-second system of units) electrostatic units in ten days operation. Therefore, for $\beta_s^T = \frac{E_B}{4\pi\rho B}$ we can get the estimation $\beta_s^T \approx 10^{-43}-10^{-45} \text{ cm}^3$ ($\rho \approx 2 \times 10^{22}$, $B \approx 10^4-5 \times 10^4$ G).

The obtained estimation for β_s^T ($\beta_s^T \sim 10^{-43}-10^{-45} \text{ cm}^3$) and the expressions (6) and (10) allow us to evaluate the mixing ratio η_{nf}^T . Recall that conventional T - and P -even polarizability of an atom can be expressed similarly (6) replacing the matrix element μ with the matrix element d (and $\eta_{nf}^T = 0$). Therefore, we can estimate $\beta_s^T \sim \beta_s \alpha \eta_T$, where β_s is the conventional T - and P -even polarizability of the atom, $\alpha = \frac{1}{137}$ is the fine structure constant, and η_T is some average value for the coefficient of mixing of opposite parity levels η_{nf}^T . The estimation for η_T follows from the above: $\eta_T \sim \frac{\beta_s^T}{\beta_s \alpha} \approx 10^{-17}-10^{-19}$ (the atom polarizability is of the order $\beta_s \sim 10^{-24} \text{ cm}^3$, for example, for Xe according to [10] $\beta_s = 2.7 \times 10^{-24} \text{ cm}^3$).

Two types of T - and P -odd interactions contribute to the constant of mixing of opposite parity levels η_{nf}^T : the interaction of the electron EDM with the Coulomb field of the nucleus and the T - and P -odd interaction of the electron with the nucleus nucleons.

The spin-independent part of the T - and P -odd interaction of an electron with nucleons is described by two constants [9]: k_{1p} describes an interaction with protons and k_{1n} describes an interaction with neutrons. For example, the calculation adduced in [9] for Cs provides $\eta_T = 3.7 \times 10^{-11}(0.41k_{1p} + 0.59k_{1n})$, where the sum $(0.41k_{1p} + 0.59k_{1n}) < 5 \times 10^{-4}$. Therefore, for Cs, $\eta_T \lesssim 10^{-14}$. The same limits for the sum k_{1p} and k_{1n} were obtained from the EDM measurements for ^{129}Xe [9] $(0.4k_{1p} + 0.6k_{1n}) \lesssim 10^{-4}$.

Let us note that in the experiment [2] planned to measure the EDM of Cs atoms trapped in optical lattices it is expected to obtain the sensitivity of Cs EDM measurement of about $d_{\text{Cs}} \approx 3 \times 10^{-25} e \text{ cm}$. This value of the atom EDM provides to improve the estimation for η_T and to get limits $\eta_T \lesssim 10^{-16}$ and the sum of k_{1p} , $k_{1n} \lesssim 5 \times 10^{-6}$.

As was shown above, the experiments studying β_s^T provide for a mixing coefficient the value $\eta_T \lesssim 10^{-17}-10^{-19}$. Therefore, these experiments give hope to reduce (three orders) the estimations for the sum of k_{1p} , k_{1n} (it is expected to be $\lesssim 10^{-7}-10^{-9}$). This value for k_{1p} , k_{1n} is significantly lower than the limit that could be obtained from the measurements of the atom dipole moment that have been done earlier (see, for example, [9]) and from the experiment proposed in [2].

Let us consider now what limits for the electron EDM d_e can be obtained studying the effect [7]. To estimate the contribution from d_e to the polarizability $\beta_s^T \sim \beta_s \alpha \eta_T$ let us use the connection of mixing coefficient η_T^e (caused by the electron EDM d_e) with the atom EDM d_A induced by the electron EDM d_e : $d_A \sim e a \eta_T^e \sim R d_e$ [9], where R is the atomic EDM enhanced factor. Therefore, $\eta_T^e \sim \frac{R d_e}{e a}$. Using the mentioned estimations for β_s^T and η_T^e we obtain $d_e \sim \frac{a \beta_s^T}{\beta_s \alpha R} e \text{ cm}$; i.e., $d_e \sim 10^{-27}-10^{-30} e \text{ cm}$ ($\beta_s^T \approx 10^{-43}-10^{-45} \text{ cm}^3$, $R \approx 10^2-5 \times 10^2$). It should be remarked that the upper limit $d_e \lesssim 1.6 \times 10^{-27} e \text{ cm}$ follows from the experiments with Tl [4].

Thus, studying the effect [7] experimentally we could get more strict (three or four orders) limits for constants, which describe T - and P -odd interactions of an electron with nucleons and for d_e . Such an improvement of estimations constrains theories beyond the standard model. To study the effect [7], one could use different atoms (molecules) and substances (for example, ferroelectric crystals providing very high electric fields for heavy atoms) and this study does not require target cooling to ultralow temperatures (1 K and lower). Spins of atoms (molecules) can be nonpolarized or atoms (molecules) can be spinless.

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