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# Electric dipole moment of atoms due to parity and time-reversal violation and its implications for physics beyond the Standard Model

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## 1. Introduction

For a non-degenerate quantum mechanical system to possess a permanent electric dipole moment (EDM), there must be a simultaneous violation of the parity (P) and time-reversal (T) symmetries [1].

An atomic EDM can arise due to :

(i) intrinsic EDM on an electron,

(ii) P and T violating electron-nucleon interactions,

(iii) P and T violating electron-electron interactions,

(iv) intrinsic EDM on a nucleon,

(v) P and T violating nucleon-nucleon interaction.

While all of the afore-mentioned sources of atomic EDM are interesting in their own right, only the first two cases have attracted serious attention so far [1,2]. The study of the EDM of atoms is useful from the point of view of particle physics because it can throw light on T or CP violation not just in the hadron but the lepton and the lepton-hadron sectors as well.

## 2. Theory of atomic EDM

Consider an atom which possesses a permanent EDM. If the atom is placed in an electric field $\vec{\varepsilon}$, then the total Hamiltonian can be written as

$$H_T = H + H_{EDM} - \vec{D}_T \cdot \vec{\varepsilon}$$

where H is the atomic Hamiltonian, $H_{EDM}$ is a P and T violating interaction,

$$\vec{D}_T = \vec{D}_{ind} + \vec{D}_{int}$$

where $\vec{D}_{ind}$ is the electric dipole moment of the atom induced by the electric field and $\vec{D}_{int}$ is the electric dipole moment of the atom due to an intrinsic electric dipole moment in the electron or the nuclear sector.

Keeping only terms that are linear in the electric field, we can write the first and second order shifts in energy as

$$\Delta E^{(1)} = \langle \Psi_0 \mid \vec{D}_{int} \mid \Psi_0 \rangle \cdot \vec{\varepsilon} \qquad \text{and}$$

$$\Delta E^{(2)} = \sum_N \frac{\langle \Psi_0 \mid H_{EDM} \mid \overline{\Psi}_N \rangle \langle \overline{\Psi}_N \mid \vec{D}_{ind} \mid \Psi_0 \rangle}{E_0 - E_N} \cdot \vec{\varepsilon} + cc,$$

where $\Psi_0$ is the atomic state and $\overline{\Psi}_N$ refers to intermediate states with parity opposite to that of $\Psi_0$.

The EDM of the atom in the state $\Psi_0$ can thus be written as

$$\vec{D}_a = \vec{D}_a^{(0)} + \vec{D}_a^{(1)}$$

where

$$\vec{D}_a^{(0)} = \langle \Psi_0 \mid \vec{D}_{int} \mid \Psi_0 \rangle$$

and

$$\vec{D}_a^{(1)} = \sum_N \frac{\langle \Psi_0 \mid H_{EDM} \mid \overline{\Psi}_N \rangle \langle \overline{\Psi}_N \mid \vec{D}_{int} \mid \Psi_0 \rangle}{E_0 - E_N} + cc.$$

The possible existence of an atomic EDM due to the intrinsic EDM of the electron and a scalar-pseudo-scalar electron-nucleon interaction have been studied fairly extensively. We first consider the EDM of the atom arising from the intrinsic EDM of the electron. It was first shown by Schiff [3] that the EDM of the atom is zero non-relativistically even if the electron is assumed to have an intrinsic EDM. Sandars [4] has later shown that the EDM of the atom resulting from the intrinsic EDM of the electron is entirely due to relativistic effects.

A P and T violating electron-nucleon scalar-pseudoscalar interaction can be written as

$$H_{EDM} = \frac{G_F}{\sqrt{2}} \sum_{e,n} (\overline{\psi}_n \psi_n)(\overline{\psi}_e i\gamma_5 \psi_e).$$

Treating the nucleons non-relativistically and the electrons relativistically, we get

$$H_{EDM} = i\frac{G_F}{\sqrt{2}} C_S \sum_e \beta\gamma_5 \rho_N(r),$$

where $G_F$ is the Fermi coupling constant, $C_S$ is the scalar-pseudoscalar coupling constant, $\rho_N(r)$ is the nuclear density, $\beta$ and $\gamma_5$ are the usual Dirac matrices.

Comments

1. The contribution to the EDM of an atom arising from the afore-mentioned interaction comes only from $D_a^{(1)}$.

2. There have been preliminary studies of an atomic EDM resulting from a tensor-pseudo tensor interaction [5].

3. It appears that the possibility of an atomic EDM being produced by P and T violating interactions in the nuclear sector has not been considered very seriously so far.

## 3. Status of atomic EDM and implications for particle physics

The results of atomic EDM experiments on cesium and thallium [6,7], combined with the many-body calculations on those two atoms [8,9], yield the following values for the intrinsic EDM of the electron :

$$\begin{aligned} d_e &= (0.14 \pm 0.54 \pm 0.14) \times 10^{-25} \text{ e cm (from cesium)} \\ &= (-2.7 \pm 8.3) \times 10^{-27} \text{ e cm (from thallium)} \end{aligned}$$

The enhancement factor (ratio of the atomic EDM to the electron EDM) for cesium was found to be 123.4 with approximately a five percent uncertainty [8]. There have been other less accurate theoretical estimates of the same quantity [10].

The enhancement factor for thallium has a much larger uncertainty [9] as it is considerably more difficult to determine the valence-core correlation for that atom than it is for cesium. The scalar-pseudoscalar coupling constant obtained by the results of experiment and theory [11,12] for atomic cesium is

$$C_S = (4.09 \pm 15.23 \pm 4.09) \times 10^{-4}.$$

The tensor-pseudotensor coupling constant can similarly be extracted from mercury [5,13]. Its value is

$$C_T = (-1.2 \pm 2.5) \times 10^{-7}.$$

The limits obtained on $d_e$ from atomic physics are consistent with Left-Right symmetric, supersymmetric, E6 [14] and multi-Higgs [15] models.

The Kobayashi Maskawa model predicts $d_e \sim 10^{-37}$ e-cm [14].

The effects of P and T violating electron-nucleon interaction have recently been studied in multi-Higgs doublet and leptoquark models [2,16]. At the tree level these interactions arise due to : (1) the exchange of a neutral spin-zero Higgs boson, (2) the exchange of a vector leptoquark, (3) the exchange of a scalar leptoquark. It was found that, in the multi-Higgs doublet models, the contribution of the scalar-pseudoscalar interactions to the atomic EDM can exceed the contribution of the electron EDM for a certain range of parameters. In the leptoquark models the contribution of the tensor-pseudo tensor interaction is the dominant one in closed-shell atoms such as mercury and xenon. Fischler et al [17] have carried out a fairly comprehensive study of the different interactions that can give rise to an atomic EDM using the Minimal Supersymmetric Standard Model. They find that for a supersymmetry breaking scale of 100Gev, the CP violating phases that are responsible for the electric dipole moments of the neutron and closed shell atoms must be less than $\sim 10^{-2}$.

The study of atomic EDMs is certainly a promising avenue for exploring physics beyond the Standard Model. An improvement of the bounds of the various quantities described earlier can provide crucial information about the validity of a large number of particle physics models.

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## Discussion

R. Raja : Your elegant derivation showing that the EDM of a particle violates P and T does not apply to a water molecule, since water molecule has two energy levels which are degenrate. How does one know that a similar effect does not happen in the neutron which is made of two down quarks and one up quark?

B.P. Das : You are right, My derivation applies only to non-degenerate systems. There are several molecules which possess a permanent electric diple moment (EDM) because of mixing of states of opposite parity that are degenerate. I am afraid I can't throw much light on the second part of your question.