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CP violating electron-nucleon interactions in multi-Higgs doublet and leptoquark models

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CP violating electron-nucleon interactions and the resulting atomic EDM are studied in several models. In the standard model these interactions are very small and are well below the experimental upper bounds. In multi-Higgs doublet models, the four-fermi interactions, $\bar{N}N\bar{e}\gamma_5 e$ and $\bar{N}\gamma_5 N\bar{e}e$, can be quite large. In some range of parameters, the contribution of these interactions to the atomic EDM can exceed the contribution of the electron EDM. In leptoquark models the contribution from the tensor interaction, $\bar{N}\sigma_{\mu\nu}N\bar{e}\sigma_{\mu\nu}\gamma_5 e$, is always the domimant one.

Up to now CP violation has only been discovered in the neutral kaon system[1]. In order to isolate the source (or sources) responsible for CP violation, it is important to find CP violation in other systems. Measurement of electric dipole moments (EDM) of atoms d_A is a very promising enterprise. A non-zero EDM of an atom will signal CP violation. Theoretical calculations of atomic EDM are complicated because there are different contributions coming from the nucleon EDM d_N, the electron EDM d_e, the CP violating nucelon-nucleon and electron-nucleon interactions. It is difficult to separate individual contribution from experimental measurement in a model independent way. However, in a given model of CP violation different contributions can be calculated and the domimant contribution can be isolated. Moreover there is hope that a study of a number of different atoms will assist in entangling the contributions of the different interactions.

There have been extensive studies of the neutron EDM[2], the electron EDM[3] and the CP violating nucleon-nucleon interactions[4] in models of CP violation. In this paper we focus on CP violating electron-nucleon interactions in several models. A similar study in two-Higgs doublet model has recently been carried out in Ref.[5]. There are three types of CP violating electron-nucleon four-fermi interactions, $\frac{G_F}{\sqrt{2}}c_T i\bar{N}\sigma_{\mu\nu}N\bar{e}\sigma^{\mu\nu}\gamma_5 e$, $\frac{G_F}{\sqrt{2}}c_P i\bar{N}\gamma_5 N\bar{e}e$, $\frac{G_F}{\sqrt{2}}c_S i\bar{N}N\bar{e}\gamma_5 e$. Note that since $\sigma_{\mu\nu}\gamma_5 = \frac{i}{2}\sigma^{\alpha\beta}\epsilon_{\mu\nu\alpha\beta}$, the terms $\bar{N}\sigma_{\mu\nu}\gamma_5 N\bar{e}\sigma_{\mu\nu}e$ and $\bar{N}\sigma_{\mu\nu}N\bar{e}\sigma_{\mu\nu}\gamma_5 e$ are identical. Significant upper bounds on the EDM of various atoms have been obtained[6–10]. From these upper bounds, constraints on the parameters c_T , c_P , c_S can be obtained[11–13]. From measurements on TlF it is found that $c_T = (1.7\pm3.0)\times10^{-7}$ and $c_S = (5.4\pm9.2)\times10^{-6}$[6]. The constraint on c_P is weaker by about an order of magnitude. Comparable results come from ^{199}Hg[7] and Cs[8]. The measurement on Tl by Abdullah et al.[9] has improved these bounds by about an order of magnitude[13].

To isolate the dominant contribution to the atomic EDM, we need to compare the relative strength of different contributions. The neutron EDM does not contribute to the atomic EDM significantly because experiments have put very stringent bound on the neutron EDM ($d_n < 1.2 \times 10^{-25} ecm$[14]). In most models of CP violation the proton EDM is of the some order of magnitude as that of neutron. This implies that the proton EDM will have negligible contribute to the atomic EDM also. In many models, the contribution of the CP violating nucleon-nucleon interactions to the atomic EDM at present are below the experemental bound due to the constraint on CP violating parameters from the neutron EDM[4]. If a non-zero atomic EDM close to its present upper bound will be measured, the likely contributing sources will be from the electron EDM and the CP violating electron-nucleon interactions. To further isolate the contribution of the CP violating electron-nucleon interactions, we define the following quantities

$$r_T = \frac{d_A(from\ c_T)}{d_A(from\ d_e)}\ , \ \ r_S = \frac{d_A(from\ c_S)}{d_A(from\ d_e)}\ . \tag{1}$$

r_i determine the relative strengths of the contributions of the CP violating electron-nucleon interactions and the electron EDM to the atomic EDM. Using the theoretical calculations in Refs.[11-13], we have

$$\begin{aligned}
r_T\,(^{199}Hg) &\approx 4.1 \times 10^{-18}\frac{c_T\ ecm}{d_e}\ ,\\
r_T\,(^{129}Xe) &\approx 2.6 \times 10^{-18}\frac{c_T\ ecm}{d_e}\ ,\\
r_T\,(TlF) &\approx -1.6 \times^{-18}\frac{c_T\ ecm}{d_e}\ ,\\
r_S\,(Cs) &\approx -6 \times 10^{-21}\frac{c_S\ ecm}{d_e}\ ,\\
r_S\,(^{199}Hg) &\approx -5 \times 10^{-20}\frac{c_S\ ecm}{d_e}\ ,\\
r_S\,(^{129}Xe) &\approx -2.6 \times 10^{-20}\frac{c_S\ ecm}{d_e}\ ,\\
r_S\,(TlF) &\approx -5 \times 10^{-20}\frac{c_S\ ecm}{d_e}\ .
\end{aligned} \tag{2}$$

A similar quantity r_P can be defined for the contribution due to c_P.

In the standard KM model of CP violation, c_S is extremely small. Using the CP violating coupling $\sqrt{2} f \bar{p} p \bar{K}^0$ calculated in Ref.[15], with $f \approx -3.2 \times 10^{-7} e^{i0.03 Im\tau}$, and the CP violating $\bar{b}\bar{e}i\gamma_5 e \bar{K}^0$ coupling $Imb \sim 10^{-7} Im\tau \frac{G_F}{\sqrt{2}}$, estimated from one loop diagram, we estimate $c_S \sim 10^{-13} Im\tau$. c_P is also the same order of magnitude. Here $Im\tau = s_2 s_3 s_\delta \sim 10^{-3}$ where s_i being the KM angles. The strong CP violating θ term also generates a very small $c_S \sim 0.06\theta$ and $c_P \sim 0.02\theta$. Here we have used the $\pi\bar{e}e$ couplings calculated in Ref.[16]. When the constraint on $\theta < 10^{-9}$ from the neutron EDM[2] is used, we obtain $c_S < 6 \times 10^{-11}$ and $c_P < 2 \times 10^{-11}$. In the above two cases, c_T are also extremely small. Large c_S, c_P and c_T can be obtained in some extensions of the standard model.

In multi-Higgs doublet models, exchange of the neutral Higgs particles between quarks and the electron can induce large c_S and c_P. The relevant terms in the Lagrangian are

$$L_{H^0} = (2\sqrt{2}G_F)^{1/2}(\alpha_{d_i}\bar{D}M_D D + \beta_{d_i}\bar{D}iM_D\gamma_5 D$$
$$+ \alpha_{u_i}\bar{U}M_U U + \beta_{u_i}\bar{U}iM_U\gamma_5 U + \alpha_{l_i}\bar{e}m_e e + \beta_{l_i}\bar{e}im_e\gamma_5 e)H_i^0 \ , \quad (3)$$

where M_U and M_D are the diagonalized quark mass matrices, H_i^0 are mass eigenstates of the neutral Higgs particles. If in the weak eigenstate of Higgs particles only one of the Higgs doublets couples to up quarks, down quarks and leptons, $\alpha_{di} = \alpha_{ui} = \alpha_{li}$ and $\beta_{di} = -\beta_{ui} = \beta_{li}$. In the literature often α and β are parametrized as

$$ImZ_{ff'} = 2\alpha_f\beta_{f'} \ . \quad (4)$$

In our later discussions, we will assume that the effect of Higgs exchange is dominated by the lightest Higgs particle.

From exchange of the neutral Higgs particles between quarks and the electron gives rise to the following effective electron-quark interactions

$$H_{eff} = \frac{4G_F}{\sqrt{2}m_H^2}(m_{u_i}m_e[\bar{u}_i u_i \bar{e} i\gamma_5 e ImZ_{ul} + \bar{u}_i i\gamma_5 u_i \bar{e} e ImZ_{lu}]$$
$$+m_{d_i}m_e[\bar{d}_i d\bar{e} i\gamma_5 e ImZ_{dl} + \bar{d}_i i\gamma_5 d_i \bar{e} e ImZ_{ld}]) , \qquad (5)$$

where the subindex i is summed over u, c, t, d, s, and b. To obtain c_S and c_P, we need to calculate $< N|H_{eff}|N, \bar{e}e >$. This requires the evaluation of $< N|\bar{q}q|N >$ and $< N|\bar{q}\gamma_5 q|N >$.

To evaluate $< N|\bar{q}q|N >$, we use the pion-nucleon Sigma-term, $\sigma_{\pi N} = \bar{m} < N|\bar{u}u + \bar{d}d|N >= 45MeV$ extracted from experiments and relations of nucleon mass shift due to SU(3) breaking quark masses[17, 18]. For heavy quarks, we use

$$< N|m_h \bar{h}h|N >= - < N|\frac{\alpha_s}{12\pi}G_{\mu\nu}G^{\mu\nu}|N > +O(\frac{\mu^2}{m_h^2}) . \qquad (6)$$

The second term in the above equation will be neglected. Using $m_u = 4.2MeV$, $m_d = 7.5MeV$ and $m_s = 150MeV$, we obtain

$$m_u < p|\bar{u}u|p > = 18MeV \ , \ m_d < p|\bar{d}d|p >= 26MeV \ ,$$
$$m_u < n|\bar{u}u|n > = 14MeV \ , \ m_d < n|\bar{d}d|n >= 32MeV \ , \qquad (7)$$
$$m_s < N|\bar{s}s|N > = 247MeV \ , \ < N| - \frac{\alpha_s}{12\pi}G_{\mu\nu}G^{\mu\nu}|N >= 48MeV \ ,$$

where $N = n, p$.

$< N|\bar{q}\gamma_5 q|N >$ are determined from EMC data and are given by[18]

$$m_u < n|\bar{u}i\gamma_5 u|n > = -419MeV \ , \ m_d < n|\bar{d}i\gamma_5 d|n >= 772MeV \ ,$$
$$m_u < p|\bar{u}i\gamma_5 u|p > = 432MeV \ , \ m_d < p|\bar{d}i\gamma_5 d|p >= -748MeV \ , \qquad (8)$$
$$m_s < N|\bar{s}i\gamma_5 s|N > = -165MeV \ , \ m_h < N|\bar{h}i\gamma_5 h|N >= -63MeV \ ,$$

Combining all information gathered above, we have

$$c_S(p) = \frac{228(MeV)m_e}{m_H^2}ImZ_{ul} + \frac{640(MeV)m_e}{m_H^2}ImZ_{dl} \ ,$$

$$c_P(p) = \frac{612(MeV)m_e}{m_H^2} ImZ_{lu} - \frac{1952(MeV)m_2}{m_H^2} ImZ_{ld} \,, \qquad (9)$$

$$c_S(n) = \frac{220(MeV)m_e}{m_H^2} ImZ_{ul} + \frac{652(MeV)m_e}{m_H^2} ImZ_{dl} \,,$$

$$c_P(n) = -\frac{1088(MeV)m_e}{m_H^2} ImZ_{lu} + \frac{960(MeV)m_e}{m_H^2} ImZ_{ld} \,.$$

In the case where in the weak eigenstate of the Higgs particles only one of the Higgs doublets couples to fermions, we have

$$c_S\,(p) = 4.3 \times 10^{-8} ImZ_{ul} \frac{(100GeV)^2}{m_H^2} \,,$$

$$c_P\,(p) = -1.3 \times 10^{-7} ImZ_{ul} \frac{(100GeV)^2}{m_H^2} \,, \qquad (10)$$

$$c_S\,(n) = 4.4 \times 10^{-8} ImZ_{ul} \frac{(100GeV)^2}{m_H^2} \,,$$

$$c_P\,(n) = 10^{-7} ImZ_{ul} \frac{(100gev)^2}{m_H^2} \,.$$

We now calculate the value of r_S using the electron EDM in muiti-Higgs models calculated in Ref.[19]. Using the values in eq.(10) we would have $c_S/d_e \sim 10^{19}/ecm$. When compare this with the values in eq.(2), we see that the electron EDM dominates the contribution to the atomic EDM. If the top and electron couple to different Higgs doublets, the situation can be different. A specific example in the two Higgs doublet has been studied in detail by Barr[5]. It was shown that in some region of the parameter space, the CP violating electron-nucleon interaction dominates the contribution to the atomic EDM.

We see from eqs.(9,10) that c_P is larger than c_S in multi-Higgs doublet models and the contribution of c_P to the atomic EDM is of the same order of magnitude as c_S. In this model c_T can only be generated at loop levels and is very small.

Let us now study c_S, c_P and c_T in leptoquark models. There are several possible scalars which carry lepton and quark numbers can couple to the standard quarks and leptons. A complete list can be found in Ref.[20]. There are two leptoquark scalars can contribute to c_S, c_P and c_T at the tree level with large magnitudes. These two leptoquarks transform under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as $H_3 : (3, 2, 7/3)$ and $H_5 : (3, 1, -2/3)$, respectively. We will work out the contribution of H_3 to c_S, c_P and c_T. In a similar way, the contribution of H_5 can be worked out.

The couplings of H_3 to fermions are give by

$$L = (\lambda_3 \bar{Q}_L e_R + \lambda_3' \bar{U}_R L_L) H_3 + H.C. , \tag{11}$$

where $Q_L^T = (u_L, d_L)$ and $L_L = (\nu_{eL}, e_L)$. From eq.(11), we obtain the effective Lagrangian which is relevant for c_S, c_P and c_T,

$$L_{eff} = -\frac{1}{m_H^2}(\lambda_3 \lambda_3'^* \bar{u}_L e_R \bar{e}_L U_R + \lambda_3^* \lambda_3' \bar{e}_R u_L \bar{u}_R e_L) . \tag{12}$$

After a Fierz rearrangement, we obtain the CP violating effective Lagrangian

$$L_{eff} = -\frac{Im(\lambda_3^* \lambda_3')}{4m_H^2} i(\bar{u}\gamma_5 u \bar{e} e + \bar{u} u \bar{e}\gamma_5 e - \frac{1}{4}\bar{u}\sigma_{\mu\nu} u \bar{e}\sigma^{\mu\nu}\gamma_5 e) . \tag{13}$$

Using the values of eqs.(7,8) and $< n|\bar{u}\sigma_{\mu\nu}u|n >= -\bar{n}\sigma_{\mu\nu}n/3$, $< p|\bar{u}\sigma_{\mu\nu}u|p >= 4\bar{p}\sigma_{\mu\nu}p/3$, we compute

$$\begin{aligned} H_{eff} = \frac{G_F}{\sqrt{2}} Im(\lambda_3^* \lambda_3') \frac{(100GeV)^2}{m_H^2} i(&-300\bar{n}\gamma_5 n \bar{e}e + 9.6\bar{n}n\bar{e}\gamma_5 e \\ &+362\bar{p}\gamma_5 p\bar{e}e + 12\bar{p}p\bar{e}\gamma_5 e - 0.5\bar{n}\sigma_{\mu\nu}n\bar{e}\sigma_{\mu\nu}\gamma_5 e + 2\bar{p}\sigma_{\mu\nu}p\bar{e}\sigma_{\mu\nu}\gamma_5 e) . \end{aligned} \tag{14}$$

The contribution of H_3 to the electron EDMs is

$$d_e \approx -\frac{Im(\lambda_3^* \lambda_3')}{16\pi^2 m_H^2} m_u ln \frac{m_u^2}{m_H^2} , \tag{15}$$

From the above, we have

$$\begin{aligned} |\frac{c_T(n)}{d_e}| &\approx 5 \times 10^{20} \frac{20}{ln\frac{m_H^2}{m_u^2}} \frac{1}{ecm} , \\ |\frac{c_T(p)}{d_e}| &\approx 2 \times 10^{21} \frac{20}{ln\frac{m_H^2}{m_u^2}} \frac{1}{ecm} , \\ |\frac{c_S}{d_e}| &\approx 10^{22} \frac{20}{ln\frac{m_H^2}{m_u^2}} \frac{1}{ecm} . \end{aligned} \tag{16}$$

Comparing eq.(16) with eq.(2) we see that in all the atoms of interest, the CP violating electron-nucleon interactions dominate over the electron EDM contribution to the atomic EDM. It is interesting to note that in this model, the dominant contribution to the atomic EDM is actually from the tensor interaction c_T. In TlF the c_T contribution to the atomic EDM is about 5 times larger than that from c_S. While in ^{129}Xe and ^{199}Hg the c_T contributions are more than ten times bigger than that of the c_S contributions. Using the present bound on c_T, the CP violating parameter $Im(\lambda_3^* \lambda_3')(100GeV)^2/m_H^2$ is constrained to be less than 5×10^{-8} which is the strongest bound so far.

To summarize, we have studied CP violating electron-nucleon interactions in several models. In the standard model the contrbution of these interactions to the atomic EDM is exptremely small. In multi-Higgs doublet models the contributions from $\bar{N}N\bar{e}\gamma_5 e$ and $\bar{N}\gamma_5 N\bar{e}e$ interactions are comparable with the contribution of the electron EDM. In the leptoquark scalar models, the contribution from the tensor interaction $\bar{N}\sigma_{\mu\nu}N\bar{e}\sigma_{\mu\nu}\gamma_5 e$ is the most important one.

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