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The strange quark contribution to the neutron electric dipole moment in multi-Higgs doublet models

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Abstract

In this paper we study the strange quark contribution to the neutron electric dipole moment and compare with other contributions in multi-Higgs doublet models. We find that the stange quark contribution is significant because the strange quark color dipole moment is larger than that of the down (up) quark by a factor m_s/m_d (m_s/m_u). In the case of neutral Higgs it can be the dominant contribution to the neutron electric dipole moment.

One of the open questions of particle physics is the origin of CP violation. Heretofore CP violation has only been observed in the neutral Kaon system.[1] Even though no other CP violating system has been found, significant improvements have been made in putting an upper bound on the neutron electric dipole moment (EDM), $|D_n| < 1.2\times 10^{-25}$ ecm.[2] The measurement of the neutron EDM can play an important role in providing information about the origin of CP violation. The standard model predictes a very small $|D_n| < 10^{-31}$ ecm. [3,4] In extensions of the standard model it is possible to have neutron EDM of the same order as the experimental upper bound. CP violation due to Higgs exchange is an example of such models.[5] Recently several authors have studied some new classes of loop diagrams in multi-Higgs models which contribute significantly to the neutron EDM.[6-9] In this paper we study the strange quark contribution to the neutron EDM and find that this contribution may well be the most important contribution of all.

The strange quark can contribute to the neutron EDM if the strange quark has a color dipole moment f_s. The color dipole moment of a quark q is defined as

$$L_q = -if_q\frac{g_s}{2}\bar{q}\sigma_{\mu\nu}\gamma_5\frac{\lambda^a}{2}qG^a_{\mu\nu}, \tag{1}$$

where $G^a_{\mu\nu}$ is the gluon field strength, and λ^a is the $SU(3)_C$ Gell-Mann matrix with $a = 1,\cdots,8$. If f_s is nonzero, a CP odd $K\Sigma n$ vertex $\sqrt{2}\tilde{g}_{K\Sigma n} =< K\Sigma| - L_s|n >$ will be generated. There are several ways of estimating this matrix element. In Ref[10] by relating the matrix element to the baryon mass differences and use of PCAC, $\tilde{g}_{K\Sigma n}$ is estimated to be - $0.35f_s$(GeV). Using a different method, approximately the same number was obtained in Ref.[3]. This matrix element has also been estimated by using QCD sum rules which gives $\tilde{g}_{K\Sigma n}$ to be about one order of magnitude larger.[11] In the present calculation we will use $\tilde{g}_{K\Sigma n} = -0.35f_s$(GeV). Using the flavour SU(3) prediction for the CP even $K\Sigma$n vertex and the above estimated CP odd vertex, we have a hadronic level effective Lagrangian

$$L_{eff} = -\sqrt{2}g_{\pi NN}(2\alpha - 1)\bar{\Sigma}^- i\gamma_5 nK^- - \sqrt{2}\tilde{g}_{K\Sigma n}\bar{\Sigma}^- nK^- + H.C., \tag{2}$$

where $g_{\pi NN} = 13.5$ and $\alpha = 0.64$. The above effective Lagrangian induces a strange quark contribution to the neutron EDM given by[3]

$$D_n(s) = -\frac{eg_{\pi NN}(2\alpha - 1)\tilde{g}_{K\Sigma n}}{4\pi^2 m_N^2}m_\Sigma G(m_K^2). \tag{3}$$

The function $G(x)$ is from the loop integral. It is given explicitly in Ref[3] and is approximately 0.6. Numerically, we have

$$D_n(s) = 0.027f_s e. \tag{4}$$

There may be other long distance contributions. It is possible to generate a CP odd $\bar{N}N\pi$ vertex due to the up and down quark color dipole moments. However, as we will see, in multi- Higgs models f_q's are proportional to the quark masses. Therefore the CP odd $\bar{N}N\pi$ vertex will be suppressed by factors of $(m_u,\ m_d)/m_s$. It has also been argued[10] that in the $SU(3) \times SU(3)$ limit, there is a singularity in the function $G(x)$ of the type $ln(m_K^2)$. The contribution can be large. There is no reason to expect significant cancellation of this contribution. In the following we will limit ourselves to the strange quark contribution to the neutron EDM given by Eq.(3).

To study the strange quark contribution to the neutron EDM, we need to calculate f_s. We will concentrate on multi-Higgs doublet models. It should be noted that there are difficulties if CP is only violated spanotaneously due to complex vacuum expectation values (VEV) of the Higgs doublets. These complex VEVs will produce complex quark masses at the tree level and therefore a non-zero contribution to the strong CP violating θ-term. The experimental upper bound on the neutron EDM constrains the VEV phases to be too small to explain the observed CP violation in the neutral Kaon system. In view of this, we will consider multi Higgs doublet models in which CP violations occur both in the KM sector and the Higgs sector. As mentioned before, KM mechanism contribution to the neutron EDM is very small, and we are considering possible large contributions from Higgs sector.

In order to have CP violation due to Higgs exchange and at the same time conserve flavour in neutral current at the tree level, at least three Higgs doublets are needed as in the original model of Weinberg.[5] Let us suppose that the Higgs doublets H_1 and H_2 provide masses for down and up quarks respectively. Their Yukawa coupling to quarks can be parametrized as

$$L(Charged\ Higgs) = -\frac{1}{v_1}\bar{U}_L K M_D D_R H_1^+ - \frac{1}{v_2}\bar{U}_R M_U K D_L H_2^+ + H.C., \qquad (5)$$

and

$$L(Neutral\ Higgs) = -\frac{1}{v_1}\bar{D}_L M_D D_R H_1^0 - \frac{1}{v_2}\bar{U}_R M_U U_L H_2^0 + H.C., \qquad (6)$$

where $M_{U,D}$ are the diagonal up and down quark mass matrices, K is the KM matrix, v_i are the VEVs of the Higgs doublets, H_i^+ are the charged Higgs particles and H_i^0 are the neutral Higgs particles. In the three Higgs doublet model, there are two charged Higgs particles and five neutral Higgs particles. In general multi Higgs models require the introduction of some discrete symmetries to avoid flavour changing neutral currents at the tree level. In the case of the two Higgs doublet [redacted] model, these symmetries then ensure CP conservation. If these symmetries are softly broken in the Higgs potential it is possible to have CP violation due to neutral Higgs exchange and respect neutral flavour conservation in the Yukawa sector at the tree level.[12,13] Using the above Lagrangian for the charged Higgs contribution, we obtain at the one loop level [14]

$$f_s = \frac{G_F}{32\sqrt{2}\pi^2} m_s \left(\frac{g_s(m_H^2)}{g_s(\mu^2)}\right)^{14/23} ImZ V_{sl}^* V_{sl} (F(x_{1l}) - F(x_{2l})), \tag{7}$$

with

$$F(x) = \frac{x}{(1-x)^3}\left(-lnx - \frac{3}{2} + 2x - \frac{x^2}{2}\right), \tag{8}$$

where l is summed over u, c, t, $x_{il} = (m_l/m_{H_i})^2$, $i = 1,2$ indicate the two charged Higgs particles, V_{kj} is the KM matrix element.

The neutral Higgs exchange contribution to f_s at the one loop level is given by[15]

$$f_s = \frac{G_F}{4\sqrt{2}\pi^2} m_s \left(\frac{g_s(m_H^2)}{g_s(\mu^2)}\right)^{14/23} \frac{m_s^2}{m_H^2} ln\left(\frac{m_H}{m_s}\right)^2 ImZ_1. \tag{9}$$

There is a large contribution to f_s at the two loop level through a Barr and Zee type diagram[8], which gives (following Ref[9])

$$\begin{aligned} f_s = \frac{G_F}{16\sqrt{2}\pi^3} m_s \alpha_s(\mu^2) \left(\frac{g_s(m_t^2, m_H^2)}{g_s(\mu^2)}\right)^{\frac{14}{23}} [(f(m_t^2/m_h^2) + g(m_t^2/m_H^2)) ImZ_0 \\ -(f(m_t^2/m_h^2) - g(m_t^2/m_H^2)) Im\tilde{Z}_0]. \end{aligned} \tag{10}$$

In the above ImZ is defined by $Im\left(\frac{<H_1^- H_2^+>}{V_2^2}\right) = \frac{\sqrt{2}G_F ImZ}{q^2+m_H^2}$ and the other ImZ_i's are defined similarly as ImZ in Ref[13]. The functions f(x) and g(x) are given by

$$f(x) = \frac{1}{2}x \int_0^1 dz \frac{1-2z(1-z)}{z(1-z)-x} ln\frac{z(1-z)}{x}, \tag{11}$$

$$g(x) = \frac{1}{2}x \int_0^1 dz \frac{1}{z(1-z)-x} ln\frac{z(1-z)}{x}. \tag{12}$$

For the neutral Higgs sector the contribution from Eq.(10) dominates over that from Eq.(9) for comparable ImZ_i's.

To see the importance of the strange quark contribution to the neutron EDM let us compare it with other contributions which have been considered in the literature. We consider the neutral Higgs sector first.

i) The valence quark contribution: This method is to calculate the up or down quark EDM d_u and d_d first and then use the SU(6) relation to obtain $D_n = \frac{1}{3}(4d_d - d_u)$.

ii) The color dipole moment contribution: This contribution is due to nonzero up and down quark color dipole moments f_u and f_d. By using the SU(6) relation, one finds $D_n = \frac{e}{9}(4f_d + f_u)$.[3]

These two contributions occur at one and two loop levels in multi-Higgs models. The one loop contribution is proportional to the third powers of the light quark masses and therefore is very small. Barr and Zee find a class of two loop diagrams which give a much larger contribution $D_n(BZ)$ to the neutron EDM.[8] Inspired by Barr and Zee's work, Chang et. al., and Gunion et. al., calculated the contribution of the color dipole moments of u and d quarks to the neutron EDM $D_n(C)$.[9] They are given by Eq.(10) with proper changes of quark masses and the parameters ImZ_i.

iii) It has been noticed by Weinberg that at two loop level a CP odd operator $-\frac{1}{6}Cf_{abc}G^{\rho}_{a\mu}G_{b\rho\nu}G_{c\sigma\eta}\epsilon^{\mu\nu\sigma\eta}$ can be generated and the coeficient C is not supressed by small quark masses.[6] This operator can contribute to the neutron EDM. Using a dimensional argument one obtains the contribution of this operator to be $D_n(W) \approx \frac{MC}{4\pi}e$.

iv) The neutral Higgs contribution to the neutron EDM can also be calculated by evaluating the Higgs nucleon coupling and then calculating the neutron EDM. Using the results from Ref[16], one obtains $D_n(N) = 10^{-22}\frac{GeV^2}{m_H^2}ImZ_1ecm$. If the Higgs mass is larger than 100 GeV, this contribution will be smaller than the color dipole moment contribution.

In Ref.[9] it was shown that among the above mentioned contributions, $D_n(C)$ is about one order of magnitude larger than the valence quark contribution and a factor of two larger than the contribution from the Weinberg three gluon operator. Comparing the strange quark contribution given by Eqs.(4) and (10), we obtain $|\frac{D_n(s)}{D_n(c)}| = 1.2$. For simplicity, we use the two Higgs doublet model with soft symmetry breaking terms mentioned above for the numerical calculation. Varying m_t, m_H in the range $m_t = m_H = m_W$ to $m_t = m_H = 200$ GeV, we obtain

$$D_n = \begin{cases} 2.0 \times 10^{-26} & \sim 1.6 \times 10^{-26}ecm, \ D(C), \\ 2.0 \times 10^{-27} & \sim 1.8 \times 10^{-27}ecm, \ t - loop\ D_n(BZ), \\ 3.8 \times 10^{-27} & \sim 1.7 \times 10^{-27}ecm, \ W - loop\ D_n(BZ), \\ 1.3 \times 10^{-26} & \sim 1.0 \times 10^{-26}ecm, \ D_n(W), \\ 1.0 \times 10^{-26} & \sim 2.5 \times 10^{-27}ecm, \ D_n(N), \\ 2.5 \times 10^{-26} & \sim 2.0 \times 10^{-26}ecm, \ D_n(s). \end{cases} \tag{13}$$

We have quoted the results of $D_n(C), D_n(BZ)$ and $D_n(W)$ from Gunion et. al.[9] with $g_s(\mu) = 4\pi/\sqrt{6}, m_d(\mu) = 7MeV, \frac{m_s}{m_d} = 20$, ImZ_i at $tan\beta = 1$.[13] We see that the strange quark contribution is the largest one. With three or more Higgs doublets, numerical evaluation become more complicated because there are several unknown

ImZ_i. However one can use the experimental upper bound on the neutron EDM to constrain the parameter $ImZ_0[g(x_t) + f(x_t)] + Im\tilde{Z}_0[g(x_t) - f(x_t)]$ to be less than one.

There are similar contributions from the charged Higgs particles. Of course we should keep in mind that even with soft symmetry breaking terms, three doublets are still needed in order to have CP violation due to charged Higgs exchange. In this case, the Weinberg three gluon operator is the dominant contribution. The coefficient C is given in Ref[7]. A dimensional analysis gives

$$D_n(W) \approx 10^{-25} ImZF(x_t) \tag{14}$$

It has been pointed out that if CP is only violated spontaneously, this contribution may be larger than the experiment upper bound.[17] Since we are considering the case where CP is violated both in the KM sector and the Higgs sector, we can easily adjust the parameters to fit CP violation in the Kaon system from KM sector. In this case CP violating parameters in Higgs sector are not fixed. The upper bound on the neutron EDM can be used to constrain the parameters. One finds that $ImZF(x_t)$ has to be less than one. Comparing this contribution with the one due to strange quark color dipole moment in Eq.(7), we find,

$$|\frac{D_n(s)}{D_n(W)}| = 0.06(1 + \frac{|V_{sc}|^2}{|V_{st}|^2}\frac{F(m_c^2/m_H^2)}{F(m_t^2/m_H^2)}), \tag{15}$$

where $F(x)$ is given by Eq.(8). For most of the values of top and Higgs masses, the above ratio is of order O(0.1). We see that in this case the strange quark contribution is less important than the Weinberg three gluon operator. The valence quark and the color dipole moments of up and down quark contributions are even smaller. The relative size of the largest neutral and charged Higgs contributions is of order $O((ImZ_0, Im\tilde{Z}_0)/ImZ)$. Further information about ImZ_i is needed in order to decide which is the more important contribution.

It is clear that strange quark may contribute significantly to the neutron EDM. Had we used the QCD sum rule estimate, the strange quark effect would be about one order of magnitude larger. In the neutral Higgs sector, we have seen that the strange quark contribution is the largest one. In the charged Higgs sector the Weinberg three gluon operator contribution is large if one uses the dimensional analysis argument. However, there are studies which show that the dimensional analysis arguments may over estimate the contribution. Suppressions may occur in concrete model calculations.[18] Bearing this in mind, even in the charged Higgs sector, the strange quark may contribute significantly to the neutron EDM.

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