Fermi National Accelerator Laboratory

FERMILAB-CONF-90/264-T
NUHEP-TH-90/37
December 20, 1990

RECENT DEVELOPMENTS IN NEUTRON ELECTRIC DIPOLE MOMENT AND RELATED CP VIOLATING QUANTITIES*

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ABSTRACT

We summarize recent theoretical developments in CP violation related to the neutron electric dipole moment, chromo-electric dipole moments for quarks, chromo-electric dipole moment for gluon, and electric dipole moments for eletron and W boson.

Recent experimental improvements on measurements of the electric dipole moment of the neutron, D_N, and that of the electron, D_e, have inspired a lot of theoretical developments in CP violating models related to these quantities. Here I wish to summarize the developments since 1989. For reviews before 1989, see ref[1]. More recent reviews can be found in ref[2,3].

Experimentally, D_N was found to be $(-14 \pm 6) \times 10^{-26}$ e–cm by the Leningrad Group[4] and more recently $(-3 \pm 5) \times 10^{-26}$ e–cm by the Grenoble Group[5]. Combining the two, we shall interprete this data as setting an upper bound on $|D_N| \leq 8 \times 10^{-26}$ e–cm. For D_e the most recently published data[6] gives $(-1.5 \pm 5.5 \pm 1.5) \times 10^{-26}$. At this Conference, I was told that this limit has recently been improved by at least one order of magnitude. Therefore the upper bound on D_e is about 10^{-26}. As we shall see, due to the recent theoretical developments, these limits have imposed nontrivial constraints on various models of CP violation.

We shall start with a brief classification of various mechanisms of CP violation. In a gauge theory, the CP violation can be implanted typically into the following sources: (1)The left handed charged currents, like the standard Kobayashi-Maskawa (K-M) model[7]. The model predicts very small values for all the quantities that we are going to discuss in this talk. In a sense these quantities are good probes of the new physics beyond the standrad model. (2)The charged Higgs mixing, like the Weinberg-Branco model[8]. Since the CP violations in this type of model are typically suppressed by small Yukawa couplings, the charged Higgs does not have to be very heavy to suppress CP violation. (3)The neutral Higgs mixing between the scalar and pseudoscalar bosons, like the Lee model[9]. Typically, all models with extended Higgs sector contain a CP violating neutral Higgs subsector. (4)The right handed currents, like the left-right models[10]. Coexistence of left- and right-handed currents gives rise to a very interesting CP violating phase associated with the mixing between two currents. This CP violation does not need more

*Contribution to Parallel Session on CP Violation at 25th International Conference on High Energy Physics at Singapore in August 1990

†Research supported in part by the U.S. Dept. of Energy under contract DE–AC02–76–ER022789

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than one generation of fermions. (5)Majorana mass, like the gluino mass or the neutrino masses. (6) Supersymmetric models[11] usually contain many sources of CP violation. Typically, it is a combination of colored, charged Higgs(the squarks) exchange and majorana masses of various neutralinos. (7)Strong CP θ parameter which we are not going to discuss here.

The recent attention on D_N was generated by Weinberg[12] who emphasized a new mechanism for D_N. He showed that there is an unique gauge invariant, P-odd, and T-odd operator of dimension 6, $\mathcal{O}_G$, involving solely the gluon field strength that can be written as

$$\mathcal{O}_G = -\frac{1}{3} f^{abc} g_{\alpha\beta} \tilde{G}^a_{\mu\nu} G^{b\mu\alpha} G^{c\nu\beta} \ . \qquad (1)$$

The operator can give potentially large contribution to D_N. Compared to another important operator, the color-electric dipole moment(CEDM) operator of quark q, $\mathcal{O}_q = \tilde{G}^a_{\mu\nu} \bar{q} \frac{1}{2} \sigma^{\mu\nu} T^a q$, the operator $\mathcal{O}_G$ should be identified as the color-electric dipole moment operator of the gluon(GCEDM)[13,3].

Knowing the existence of $\mathcal{O}_G$, there are three issues to be investigated. The first one is to calculate its coefficient, $\mathcal{C}$, in a specific model of CP violation, and determine the scale at which the operator is induced. The second is to evolve, using QCD renormalization group (R.G.) equation, the operator to the low energy scale at which one can estimate its physical effect. The third is to evaluate its contribution to the D_N by calculating the corresponding hadronic matrix element. All three issues are coupled. Clearly, to include QCD corrections one needs to know the scale at which each operator is induced. The effect of the QCD R.G. correction is also very sensitive to the choice of the low energy hadronic scale. The proper hadronic scale to choose is presumably determined by the scale at which we think the hadronic matrix element can be evaluated with any confidence. The simplest way to estimate this is to use naive dimensional analysis[14]. It gives[12]

$$D_N \sim e M_\chi \zeta_{QCD}(\mu) (g_s(\mu)/4\pi)^{-3} \mathcal{C}(g_s(\mu)) \qquad (2)$$

where M_χ is the chiral symmetry breaking scale of $\sim 1.19 GeV$, μ is a hadronic scale, and ζ_{QCD} is the QCD renormalization factor. However, the method was shown to be reliable[14] for the matrix elements which involve scales near the confinement scale ($\sim$ 250 MeV). Its reliability is not clear for scale near the neutron mass or M_χ. In addition, near the confinement scale the QCD is known to be strong and the perturbative R.G. analysis is invalid there. Naive extrapolation of R.G. equation to lower energy gives a large and uncertain result. For this reason we shall take M_χ as the low energy end of the R.G. evolution in order to make numerical comparison of different models. To get an idea of how uncertain the estimate of Eq(4) is, one can compare it with another recent estimate of this matrix element[15] which obtained a value 30 times smaller than Eq(4).

Weinberg [12] showed that $\mathcal{C}$ is induced, for models with CP violating mixing of the physical neutral Higgs bosons, through a two–loop diagram with top quark loop and neutral Higgs exchange. Dicus [16] showed that for models with CP violating charged Higgs mixing, similar two loop contributions can be obtained by replacing the neutral Higgs with the charged Higgs. In that case the fermion loop contains both top and bottom quarks. He noted that the contribution is not suppressed by the fact that b-quark is much lighter than the top quark. This is a little bit surprising because using the chirality argument one naively expects the calculation to be suppressed by two powers of lighter quark mass (m_b^2) with one from the Yukawa coupling and another one from the propagator. However this mass factor turns out to be cancelled by the fermion mass singularity in the loop integral. In ref.[17] we pointed out that Weinberg mechanism may also provide appreciable contribution to the D_N for models with CP violating left-right mixing. The diagrams can be obtained by replacing the charged Higgs in the previous model with the charged gauge bosons which contain the CP violating mixing. In this case, the m_b factor from the

Yukawa coupling is replaced by the gauge coupling. As a result, left right models have the interesting feature that the lighter quark masses actually provide an enhancement factor due to the mass singularity in the loop integrals. In the supersymmetric model, the particles in the loops are the gluino, squarks, and quarks.[11]

The fermion mass singularity in the loop is of course a signal that the corresponding fermion loop should not be treated as a local operator above the the corresponding fermion mass scale. The proper way to treat this problem is to integrate out the t quark and the W boson first which induces a color electric dipole moment operator, as in eq(2), for the b quark. This operator is then QCD corrected using the R.G. technique down to the b-quark scale. The $\mathcal{O}_G$ operator is subsequently induced after the b quark is integrated out[19,18]. Therefore to calculate the QCD effect one needs the two by two anomalous dimension(a.d.) matrix of the operators $\mathcal{O}_G$ and $\mathcal{O}_q$.

A more useful basis of operators for the effective Hamiltonian are $\mathcal{O}_1(\mu) = g_s(\mu)^3\mathcal{O}_G(\mu)$ and $\mathcal{O}_2(\mu) = g_s(\mu)m_q(\mu)\mathcal{O}_q(\mu)$. The a.d. for $\mathcal{O}_1$ was calculate in ref[20]. Unfortunately, the sign of the answer was in error. Based on this wrong sign, Weinberg[12] concluded that any model with CP violation in the Higgs sector would require large finetuning to avoid the constraint from the D_N through this mechanism. The correct a.d.'s were later obtained[21] with $\gamma_{11} = \gamma_{GG} - 3\beta = -12C_A$ for $\mathcal{O}_1$ and $\gamma_{22} = \gamma_{qq} - \beta + \gamma_m = 4C_A - 16C_F$ for $\mathcal{O}_2$[22,21], where γ_{GG} is the a.d. for $\mathcal{O}_G$, γ_{qq} is the a.d. for $\mathcal{O}_q$ and $\gamma_m = -6C_F$ is the a.d. of the quark mass operator. For $SU(3)$, $C_A = 3$ and $C_F = \frac{4}{3}$. The operator $\mathcal{O}_G$ can induce the operator $\mathcal{O}_q$. This operator mixing is controlled by the a.d. $\gamma_{Gq} = 2C_A$. If one is only interested in $\mathcal{O}_G$ at low energy, this mixing is actually a higher order effect and can therefore be ignored[13].

It was later pointed out[15] that all the above a.d.'s have been calculated before by Morozov[23]. In fact he had calculated the a.d's of all the operators of dimension ≤ 8 except for the four fermion operators. Some of the other dim.6 or 8 operators can have effect as large as that of $\mathcal{O}_G$.[24]

The result $\gamma_{11} = -36$ indicates that the operator $\mathcal{O}_G$ is very suppressed by the QCD effect. This suppression is most severe in the neutral Higgs model of CP violation because $\mathcal{O}_G$ is induced at the highest scale. In spite of that, for resonable choice of CP violating parameter and Higgs masses, it can still result in D_N as large as the experimental limit.[2]

The operator $\mathcal{O}_q$ does not induce $\mathcal{O}_G$ through R.G. evolution. However, when one evolves below the threshold of the quark q, $\mathcal{O}_q$ induces an effective $\mathcal{O}_G$ through the matching condition at the threshold. In the charged Higgs models or the left right models, $\mathcal{O}_G$ is not induced until b quark is integrated out. Therefore, above the m_b scale, the QCD evolution affects only the operator $\mathcal{O}_q$ which has a much smaller suppression factor corresponding to $\gamma_{22} = \frac{-28}{3}$. In fact, for left right models, the m_q in $\mathcal{O}_2$ is m_t. Therefore setting $\gamma_m = 0$ we have $\gamma = \frac{-4}{3}$. Therefore, the QCD effect is least suppressive for the left right models.

If the CP-violation comes from the neutral Higgs boson mixing, the NEDM is estimated to be $D_N \sim 2.0 \times 10^{-21}\zeta^{NH}_{QCD}(\mu)h(m_t/M_H)(\text{Im } Z_2)$ e $-$ cm. Here, Im Z_2 is the complex phase from the mixing between scalar and pseudoscalar Higgs bosons; the function $h(m_t/M_H)$ is defined in Refs.[12,16]. For $\mu \sim 1\ GeV$, the QCD evolution factor, ζ^{NH}_{QCD}, is given by $\sim 3 \times 10^{-4}$, and D_N is about $6.0 \times 10^{-25}\text{Im}Z_2$ e $-$ cm for $m_t \sim M_H$. For the charged Higgs boson case, $\zeta^{CH}_{QCD} \sim 10^{-3}$, D_N is about $3 \times 10^{-25}\text{Im } Z_2'$ $e - cm$ for $m_t \sim M_{H^+}$. Note that the case for susy models[11] is not very different from this case. In the left-right models, assuming the right-handed scale is around TeV, one has[17] $D_N \sim 1.59 \times 10^{-19}\zeta^{LR}_{QCD}(\mu)f(m_t/M_W)\sin\xi\sin\eta$ e $-$ cm, where ξ and η are the left-right mixing angle and the CP-violation phase respectively. The function $f(x)$ is of order unity[18]. The QCD evolution factor is $\zeta^{LR}_{QCD}(1GeV) \sim 1.5 \times 10^{-3}$. We have $D_N \sim 2 \times$

$10^{-22} \sin\xi \sin\eta$ e − cm, assuming $m_t \sim M_W$. More numerical details can be found in ref.[3].

Another recent inspiring work is an observation by Barr and Zee[25]. In the neutral Higgs models of CP violation, the usual one loop mechanism for D_e is suppressed by three powers of electron mass and therefore negligible. Barr and Zee observed that this suppression factor is a one loop level accident which can be easily avoided by considering two loop contributions. They showed that the resulting D_e can be eight orders of magnitude larger than the traditional one loop mechanism. There are three follow-up calculations[26] of this mechanism with basically the same numerical conclusions.

Inspired by this observation, there are two recent works[27] which applied this mechanism to the CEDM of light quarks, D_q^c. It was found that this mechanism may be more important to D_q^c than to D_q because the diagram involves three powers of QCD coupling constant. Therefore it may also be the largest contribution to D_N in some neutral Higgs models of CP violation.

Finally we shall mention the recent developments about electric dipole moment of W, D_W. The most important physical consequence of D_W is again its contribution to D_N. There are two operators that can contribute to D_W. One of them is $SU(2)_L$ breaking and of dimension 4 and the other $SU(2)_L$ preserving and of dimension 8. Marciano and Queijeiro[28] tried to analyze this contribution model independently, they found that the upper bound for D_N of order 10^{-25} $e-cm$ could be used to place a very stringent upper bound on $D_W \leq 10^{-20}$ $e-cm$. However, they used only the dimension 4 term in their analysis for simplicity. In addition, in order to tame the divergence they have to postulate a form factor. It is interesting to ask whether such a form factor is realized in any model, or whether D_W can be larger than the above bound so that it may still be possible to measure directly in experiment.

Recent one loop analysis[29] of various models of CP violation showed that only models with right-handed current contribute and only the dimension 4 operator is induced in that case. However, it is clear that in models with two loop contributions[30], the dimension 6 operator will also be induced. A careful comparison of form factors will be needed to settle such issues. One can of course by pass the form factor issue and calculate the multiloop contribution[31] to D_N directly also.

ACKNOWLEDGEMENTS

We would like to thank the Organizers at *Rochester* − 90 for invitation. We also like to thank E. Braaten, W.-Y. Keung, T.-C. Yuan and C.-S. Li X.-G. He, A. Zee for discussions.

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