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W-Boson Electric Dipole Moment Generated at Two-Loop Level

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We calculate the W-boson electric dipole moment in the Weinberg-Higgs model in which the CP violation is mediated by charged Higgs boson exchange, and compare our results with the others given by the literature.

1. INTRODUCTION

Recent experimental upper bound [1] on the electric dipole moment (EDM) of the neutron denoted by D_n furnishes very strong constrains on different models of CP violation. However, It is also important to investigate the EDMs of other particles. In fact, 25 years ago Salzman [2] pointed out that W-boson might have intrinsic EDM $D_W = \lambda_W e/2M_W$, and suggested that if $\lambda_W \sim 1$, it could explain the observed CP violation in the neutral-Kaon system. But in the standard model, $\lambda_W = 0$ even at the two-loop level. Later, Marciano and Queijeiro [3] showed that the neutron EDM can arise from nonzero D_W through one-loop graphs in an effective field theory. Using the experimental upper bound on D_n, they predicted $|\lambda_W| \leq 10^{-3}$, which is model-independent. Therefore, in renormalizable gauge models of CP violation, it is still important to study further the W-boson EDM, and discuss the constrains on D_W by using the experimental upper bound on the neutron EDM. This question has been investigated recently by He and Mckellar [4]: they calculated the W-boson EDM at the two-loop level in the Weinberg-Higgs model [5], in which the CP violation is mediated by neutral Higgs exchange. In this paper, we discuss the W-boson EDM at the same level and in the same model, but the CP violation is mediated by charged Higgs exchange.

2. CALCULATION

In the most general effective Lagrangian [6] of the W-boson coupled to a photon, the relevant terms of the W-boson EDM can be expressed as

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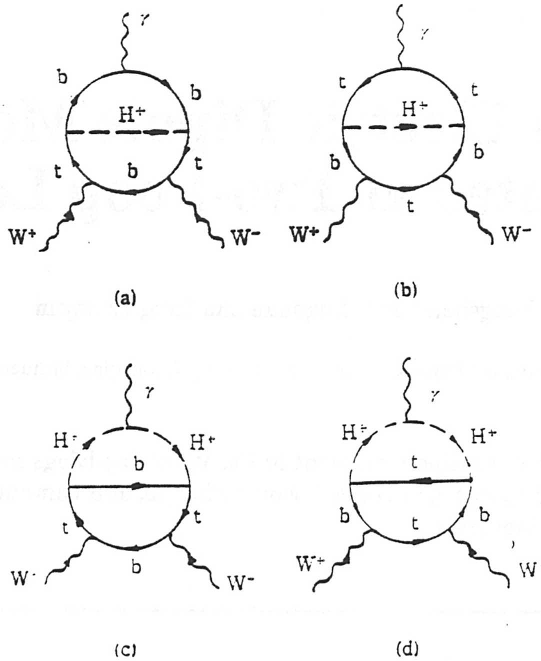

Fig. 1
The two-loop diagrams relevant to the W-boson EDM.

$$\mathcal{L}_{\text{eff.}} = ikW^+_\mu W_\nu \tilde{F}^{\mu\nu} + i\frac{\lambda}{M_W^2} W^+_{\alpha\mu} W^\mu_\nu \tilde{F}^{\nu\alpha}, \tag{1}$$

where W_μ is the W^+ boson field, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + gW_\mu \times W_\nu$, and the dual of the photon field strength is $\tilde{F}^{\mu\nu} = 1/2\, \varepsilon^{\mu\nu\alpha\beta}(\partial_\alpha A_\beta - \partial_\beta A_\alpha)$. In the momentum space, these terms can be written as

$$f_1 \varepsilon^{\mu\nu\lambda\alpha}(k_1 - k_2)_\alpha + \frac{f_2}{M_W^2}\varepsilon^{\mu\nu\beta\alpha}(k_1 - k_2)_\alpha(k_1 + k_2)^\lambda(k_1 + k_2)_\beta, \tag{2}$$

where k_1 and k_2 are the incoming and outgoing momenta of the W-boson. The form factors $f_1 = \lambda - k$ and $f_2 = \lambda/2$ are functions of $(k_1 - k_2)^2$ (the square of the momentum transfer). In the limit $(k_1 - k_2)^2 \to 0$, the EDM D_W can be expressed [6] in the unit of $e/2M_W = 1.2 \times 10^{-16}$e-cm,

$$D_W = (f_1 - 4f_2)(e/2M_W), \tag{3}$$

It is well known that the W-boson EDM D_W can arise at least through two-loop Feynman diagrams in the Weinberg-Higgs model in which the CP violation is mediated by neutral Higgs-boson exchange or by charged Higgs-boson exchange. The relevant two-loop diagrams are shown in Fig.1. Direct calculation gives the form factor $f_{1,2}$:

$$f_{1,2} = \frac{-ieg^2}{128\pi^4}\frac{m_b m_t}{M_W^2} I_m(a^*b)H_{1,2}, \tag{4}$$

where the Kobayashi-Maskawa matrix elements have been assumed as $V_{tb} = 1$, $H_i = h_i(\sigma_b,\sigma_t,\sigma_H) + h'_i(\sigma_b,\sigma_t,\sigma_H)$, $(i = 1,2)$. The functions $h_{1,2}$ and $h'_{1,2}$ are given by the following integrals ($\sigma_b = m_b/M_W$, $\sigma_t = m_t/M_W$, $\sigma_H = m_H/M_W$)

$$h_1(\sigma_b,\sigma_t,\sigma_H) = \int_0^1 dx \int_0^1 d\xi_1 \int_0^{\xi_1} d\xi_2 Q_b x(1+x)\xi_2[x(1-\xi_2+x\xi_{21})\sigma_b^2 + x(1-x)\xi_2\sigma_t^2$$
$$+ (1-\xi_1)(1-x)\sigma_H^2 + x(1-x)\xi_{21}(1+\xi_{21})]^{-1} + (Q_b \to Q_t, \sigma_b \longleftrightarrow \sigma_t), \tag{5}$$

$$h_2(\sigma_b,\sigma_t,\sigma_H) = \frac{\pm 1}{2}\int_0^1 dx \int_0^1 d\xi_1 \int_0^{\xi_1} d\xi_2 Q_b x^3 \xi_2\xi_{12}(1-\xi_{12})(1-x)[x(1-\xi_2+x\xi_{21})\sigma_b^2$$
$$+ x(1-x)\xi_2\sigma_t^2 + (1-x)(1-\xi_1)\sigma_H^2 + x(1-x)\xi_{21}(1+\xi_{21})]^{-2}$$
$$+ (Q_b \to Q_t, \sigma_b \longleftrightarrow \sigma_t), \tag{6}$$

and

$$h_1'(\sigma_b,\sigma_t,\sigma_H) = \int_0^1 dx \int_0^1 dy \int_0^1 d\xi_1 \int_0^{\xi_1} d\xi_2 x^2(1-y)\xi_2\{x(1-y)[(1-\xi_{12})\xi_{12}l(x,y)$$
$$-(1-\xi_1+\xi_{12}l(x,y))\sigma_b^2 - l(x,y)\xi_2\sigma_t^2] - l(x,y)(1-\xi_1)\sigma_H^2\}^{-1} + (\sigma_b \longleftrightarrow \sigma_t), \tag{7}$$

$$h_2'(\sigma_b,\sigma_t,\sigma_H) = \frac{-1}{2}\int_0^1 dx \int_0^1 dy \int_0^1 d\xi_1 \int_0^{\xi_1} d\xi_2 x^3(1-y)^2\xi_2 l(x,y)\xi_{12}(1-\xi_{12})\{x(1-y)$$
$$\times[(1-\xi_{12})\xi_{12} \times l(x,y) - (1-\xi_1+\xi_{12}l(x,y))\sigma_b^2 - l(x,y)\xi_2\sigma_t^2]$$
$$- l(x,y)(1-\xi_1)\sigma_H^2\}^{-2} + (\sigma_b \longleftrightarrow \sigma_t), \tag{8}$$

where Q_b and Q_t denote the charge of b quark and t quark, respectively, in the unit of e, $\xi_{ij} \equiv \xi_i - \xi_j$, and $l(x,y) \equiv 1 - x + xy$.

$\mathrm{Im}(a^*b)$ in (4) is the model-dependent parameter of CP violation and can be expressed as [5,7]

$$\mathrm{Im}(a^*b) = \sqrt{2}\, G_F \mathrm{Im}(Z_2) m_b m_t. \tag{9}$$

The numerical values of the integrals $h_{1,2}$ and $h_{1,2}'$ are given in Tables 1 and 2 for several values of m_t and m_H.

As the same parameter $\mathrm{Im}(Z_2)$ appears in the formulae of both D_W and D_n, by using the experimental upper bound on D_n, we can place a limit on the parameter $\mathrm{Im}(Z_2)$, and consequently place a limit on D_W. We know that there are different ways of estimating the contribution of the charged Higgs to the neutron EDM; therefore we can obtain different limits on parameter $\mathrm{Im}(Z_2)$. The resulting limits on D_W are given in Table 3. Although we know that the recent experimental result [1] is $|D_n| \leq 8 \times 10^{-26}$e-cm, for comparison, in all the above calculations of D_W we have assumed $|D_n| < 1.2 \times 10^{-25}$e-cm, which is consistent with Ref.[4].

3. CONCLUSION

Table 3 shows that the upper bound on the W-boson EDM is relatively small in the Higgs-boson-nucleon Coupling model of the neutron EDM, and that in any model, for $m_t \gg m_H$, the upper

Table 1

Numerical values of integrals of $h_{1,2}$ and $h'_{1,2}$ $(m_t \gg m_H)$.

$m_t >> m_H$	h_1	h'_1	h_2	h'_2
$m_t = 200\text{GeV}$ $m_H = 10\text{GeV}$	-9.43	14.4	$+2.03$	-28.8
$m_t = 150\text{GeV}$ $m_H = 10\text{GeV}$	-14.70	3.31	$+3.39$	-6.61
$m_t = 100\text{GeV}$ $m_H = 10\text{GeV}$	-18.7	9.22	$+4.42$	-18.4

Table 2

Numerical values of integrals of $h_{1,2}$ and $h'_{1,2}$ $(m_H \gg m_t)$.

$m_H >> m_t$	h_1	h'_1	h_2	h'_2
$m_t = 100\text{GeV}$ $m_H = 600\text{GeV}$	0.250	-0.013	$+0.083$	-0.001
$m_t = 100\text{GeV}$ $m_H = 800\text{GeV}$	0.048	-0.012	$+0.016$	-0.002
$m_t = 100\text{GeV}$ $m_H = 1\text{TeV}$	-0.003	-0.006	$+0.003$	-0.0002

bound on D_W is several orders of magnitude larger than that for $m_H \gg m_t$. Moreover, in comparing our results with those of He and Mckellar [4], it is found that our results are close to theirs when $m_t \gg m_H$, but are several orders smaller than theirs when $m_H \gg m_t$. As it was estimated in Ref.[4], it is due to the suppression of a factor proportional to the light-quark mass. But the prediction in Ref. [4] is not completely correct for $m_t \gg m_H$. Secondly, in compàring with the results obtained by Marciano and Queijeiro [3], ours are also small, which is not surprising because they calculated the neutron EDM generated through one-loop graphs with the first term in (1) as the effective interaction term. To regulate the divergent integral, they introduced a form factor to cut off the integral, and then obtained the upper bound on the W-boson EDM by using the experimental upper bound on the neutron EDM. However, since it is in a special gauge model of CP violation that we carried out the calculation, the results are also affected by the constrains on the model parameters that arise from the theoretical prediction on the neutron EDM in such model. So they are generally smaller than Marciano's. Of course, to compare thoroughly our results with Marciano's, one should directly calculate the form factor of W-boson EDM through one-loop graphs in the model where the first term in (1) is taken as the effective interaction term. Further analysis on this will be made in another paper [11].

Table 3
Upper bound on D_W.

Calculation value of NEM / t-quark, Higgs mass value	Valence quark model [8]	Higgs-nucleon coupling [9]	Weinberg gluon operator [7;10]
$m_t = 200\,\mathrm{GeV}$ $m_H = 10\,\mathrm{GeV}$	$\lvert D_W\rvert < 6.3 \times 10^{-20} e$-cm	$\lvert D_W\rvert < 6.3 \times 10^{-23} e$-cm	$\lvert D_W\rvert < 1.3 \times 10^{-21} e$-cm
$m_t = 150\,\mathrm{GeV}$ $m_H = 10\,\mathrm{GeV}$	$\lvert D_W\rvert < 4.8 \times 10^{-22} e$-cm	$\lvert D_W\rvert < 4.8 \times 10^{-25} e$-cm	$\lvert D_W\rvert < 9.6 \times 10^{-23} e$-cm
$m_t = 100\,\mathrm{GeV}$ $m_H = 10\,\mathrm{GeV}$	$\lvert D_W\rvert < 6.8 \times 10^{-21} e$-cm	$\lvert D_W\rvert < 6.8 \times 10^{-24} e$-cm	$\lvert D_W\rvert < 1.4 \times 10^{-22} e$-cm
$m_t = 100\,\mathrm{GeV}$ $m_H = 600\,\mathrm{GeV}$	$\lvert D_W\rvert < 1.3 \times 10^{-23} e$-cm	$\lvert D_W\rvert < 1.3 \times 10^{-26} e$-cm	$\lvert D_W\rvert < 2.6 \times 10^{-25} e$-cm
$m_t = 100\,\mathrm{GeV}$ $m_H = 800\,\mathrm{GeV}$	$\lvert D_W\rvert < 2.9 \times 10^{-24} e$-cm	$\lvert D_W\rvert < 2.9 \times 10^{-27} e$-cm	$\lvert D_W\rvert < 5.8 \times 10^{-26} e$-cm
$m_t = 100\,\mathrm{GeV}$ $m_H = 1\,\mathrm{TeV}$	$\lvert D_W\rvert < 3.8 \times 10^{-24} e$-cm	$\lvert D_W\rvert < 3.8 \times 10^{-27} e$-cm	$\lvert D_W\rvert < 7.7 \times 10^{-25} e$-cm

We conclude that depending on the constrains furnished on the parameters of CP violation by the experimental upper bound on the neutron EDM in different ways of calculating the neutron EDM, and on the different cases of assumed values of m_t and m_H, the upper bound on the D_W is constrained to be less than 6.3×10^{-20}-2.9×10^{-27}e-cm in our model.

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