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Rapid Communications

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Neutron electric dipole moment from charged-Higgs-boson exchange

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Weinberg has discovered a dimension-6 operator which makes a very large contribution to the neutron electric dipole moment through the exchange of a neutral Higgs boson. We show here that charged-Higgs-boson exchange, if it violates *CP*, can make an equally large contribution to the same operator.

Very recently, Weinberg[1] has discovered a dimension-6 operator which violates *CP* through the exchange of a neutral Higgs boson and which makes a very large contribution to the neutron electric dipole moment unless the parameter which controls the strength of the *CP* violation is unnaturally small. The operator, which violates parity and time-reversal invariance, is

$$\mathcal{O}=-\frac{C}{6}f_{abc}G_a^{\mu\rho}G_{b\rho}^{\nu}\tilde{G}_{c\mu\nu}\,, \tag{1}$$

where $G_a^{\mu\nu}$ is the gluon field-strength tensor and $\tilde{G}_a^{\mu\nu}$ is its dual, $\epsilon^{\mu\nu\alpha\beta}G_{a\alpha\beta}$.

The coefficient C can be calculated from the three-gluon part of (1) by considering a top-quark loop with a Higgs-boson exchange as shown in the diagrams of Fig. 1. The Higgs-boson propagator is given by

$$(\lambda_2)^{-2}\int d^4x\,e^{iq\cdot x}\langle 0|(\phi_2(x)\phi_2(0))_+|0\rangle \simeq \sqrt{2}G_FZ_2/(q^2-m_H^2)\,, \tag{2}$$

where Z_2 is a complex parameter. The *CP*-violating contribution is given by the diagrams with $(1+\gamma_5)$ at each Higgs-boson vertex plus the same diagrams with $(1-\gamma_5)$ at each Higgs-boson vertex and Z_2 replaced by Z_2^*. A straightforward calculation gives, for the T-matrix element,

$$T=\tfrac{4}{3}\sqrt{2}G_Fg_s^3(4\pi)^{-4}\,\mathrm{Im}Z_2f_{abc}\epsilon_\mu^a(p_1)\epsilon_\nu^b(p_2)\epsilon_\alpha^c(-p_1-p_2)$$
$$\times[(p_1-p_2)^\alpha\epsilon^{\mu\nu\rho\sigma}p_{1\rho}p_{2\sigma}+2(p_1^\nu\epsilon^{\mu\alpha\rho\sigma}p_{1\rho}p_{2\sigma}+p_2^\mu\epsilon^{\nu\alpha\rho\sigma}p_{1\rho}p_{2\sigma})]h(m_t,m_H)\,, \tag{3}$$

where g_s is the QCD coupling constant, m_t is mass of the top quark, the p and ϵ are the momenta and polarizations of the gluons as given in Fig. 1, and

$$h(m_t,m_H)=\frac{m_t^4}{4}\int_0^1dx\int_0^1du\frac{u^3x^3(1-x)}{[m_t^2x(1-ux)+m_H^2(1-u)(1-x)]^2}\,. \tag{4}$$

Setting (3) equal to the three-gluon matrix element of (1) gives

$$C=2\sqrt{2}G_Fg_s^3(4\pi)^{-4}\,\mathrm{Im}Z_2h(m_t,m_H)\,. \tag{5}$$

Weinberg[1] argues that this gives a contribution to the neutron electric dipole moment of

$$d_n\simeq 4\times 10^{-21}e\xi\,\mathrm{Im}Z_2h(m_t,m_H)\ \mathrm{cm}\,, \tag{6}$$

where ξ is a renormalization factor to account for the running of C from scale m_t to low energy.[2] Even if ξ is unity

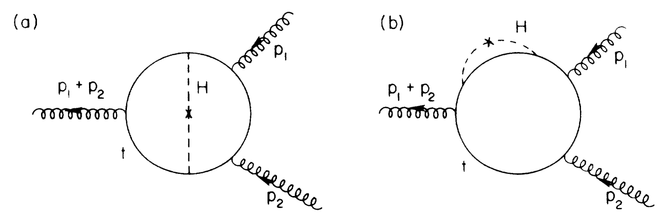

FIG. 1. The Feynman diagrams used to calculate the coefficient C of the dimension-6 operator given in Eq. (1). All permutations of the external gluon lines are implied. The solid line is a top quark if the Higgs boson H is neutral; if H is charged then the quark line is a bottom or top as appropriate.

the experimental bound on d_n requires ImZ_2 to be unnaturally small.

The purpose of this Rapid Communication is to point out that if the charged-Higgs-boson sector is sufficiently rich to allow *CP* violation in charged-Higgs-boson exchange then that will contribute to C in an amount at least equal to the contribution of the neutral Higgs boson given above.

For charged Higgs bosons the contribution to C can again be calculated from the diagrams in Fig. 1 if the top quarks on one side of the loop are replaced by bottom quarks. The couplings of the charged Higgs bosons are still both $(1+\gamma_5)$ [plus the same diagrams with $(1-\gamma_5)$] but the coupling at one vertex is proportional to the bottom mass m_b while the other still goes as m_t.[3,4] The trace around the loop brings in another factor $m_b m_t$. The same calculation that gave (3) above now reproduces (3) and (6) with Z_2 replaced by Z_+ for a charged Higgs boson and $h(m_t,m_H)$ replaced by

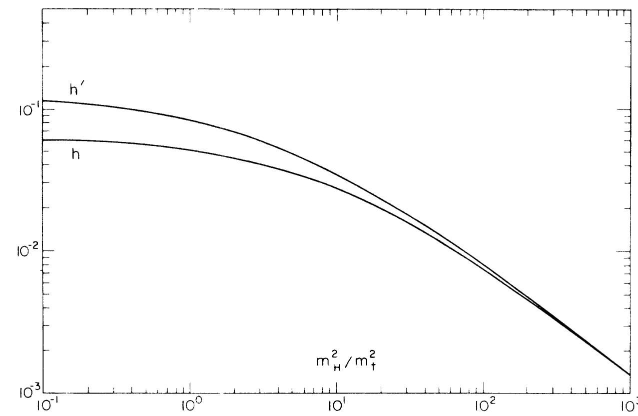

FIG. 2. The dependence of the functions h [Eq. (4)] and h' [Eq. (7)] on the ratio of the Higgs-boson mass to the top mass. Note that the definition of h is smaller by a factor of 2 than that given in Ref. 1.

$$h'(m_b,m_t,m_H)=\frac{m_b^2 m_t^2}{4}\int_0^1 dx\int_0^1 du\frac{u^3x^3(1-x)}{[m_b^2ux(1-x)+m_t^2x(1-u)+m_H^2(1-x)(1-u)]^2}+(m_b\leftrightarrow m_t)\,, \tag{7}$$

where now m_H refers to the mass of the charged Higgs boson. The first term in (7) comes from those diagrams where three of the quark lines in Fig. 1(a) are bottom quarks. The diagrams of Fig. 1(b) add to zero here as they did in the neutral-Higgs-boson case; it is easy to see this must be true since they cannot contribute to the tensor structure of (3).

Equation (7) shows that the expectation that the charged-Higgs-boson contribution is suppressed by factors of m_b/m_t is true for the diagrams where more of the lines are top quarks but not true for the first term where the integral is infrared divergent if m_b is zero. This infrared divergence can be seen in Fig. 1(a) if the quarks on the right-hand half of the diagram are bottom quarks. Call the integration momenta q and k and let the Higgs-boson momentum be $q-k$. Then the bottom-quark momenta can be taken as k, $k+p_1$, and $k+p_1+p_2$, which, if m_b is neglected, give denominators k^2, $k\cdot p_1$, and $k\cdot(p_1+p_2)$ in the small-k limit.

A graph of the functions h and h' is given in Fig. 2 where the values were determined by numerically integrating (4) and (7). h' is a factor of 2 larger than h for $m_H^2 \ll m_t^2$; for $m_H^2 \gg m_t^2$ both functions approach

$$h=h'\rightarrow\frac{1}{4}\frac{m_t^2}{m_H^2}\left[\ln\frac{m_H^2}{m_t^2}-\frac{3}{2}\right].$$

In fact, since empirically $m_t^2 \gg m_b^2$, h' is accurately given by

$$h'\simeq\frac{1}{4}\frac{m_t^2 m_H^4}{(m_H^2-m_t^2)^3}\left[\ln\frac{m_H^2}{m_t^2}-\frac{3}{2}+2\frac{m_t^2}{m_H^2}-\frac{1}{2}\frac{m_t^4}{m_H^4}\right], \tag{8}$$

for all values of m_H. No such simple expression exists for h. Because the result for h' is essentially independent of m_b, we may also have contributions where the b quark is replaced by an s or d. To the extent that the calculations above are valid for light quarks, neglecting these contributions exactly compensates for our neglect of Kobayashi-Maskawa mixing angles.

It is certainly easy to construct models with enough neutral scalars for *CP* violation to occur through neutral-Higgs-boson exchange but not enough charged scalars for it to occur through charged-Higgs-boson exchange. Thus *CP* violation is probably more likely to occur through neutral exchange, and, if it occurs through charged exchange, it will also occur through neutral exchange.[4] What we have shown is that the contribution to the neutron electric dipole moment from charged-Higgs-boson exchange, if the Higgs structure is sufficiently complicated for it to exist, is potentially as large as the contribution from neutral-Higgs-boson exchange.

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[1] S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).
[2] The function ξ has been calculated by J. Dai and H. Dykstra and a paper is in preparation. They find ξ to be much larger than one.
[3] S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
[4] N. G. Deshpande and E. Ma, Phys. Rev. D **16**, 1583 (1977).