P and *CP* nonconservation through Higgs exchange in gauge models with right-handed charged currents*

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The recent proposal of Weinberg that *CP* violation occurs through the exchange of *charged* Higgs bosons is examined in detail for gauge models with right-handed charged currents. We find that parity must be violated as well through the exchange of *neutral* Higgs bosons. In a five-quark model, this effect could be considerably bigger than that of the usual weak interaction, and should be looked for in $\psi' \to \psi\pi\pi$ and $\psi' \to \psi\pi^0$ as a test of this whole theoretical framework. Other interesting phenomena are the enhanced production of certain Higgs bosons and a value for the neutron electric dipole moment which is within experimental limits.

I. INTRODUCTION

Recently, Weinberg[1] proposed that *CP* nonconservation is solely due to the exchange of *charged* Higgs bosons. In the standard four-quark gauge model,[2] this can be achieved at the expense of having three or more Higgs scalar doublets, although only one is needed for quark and vector-boson masses. In this scheme the value of the neutron electric dipole moment is expected to be of the order 10^{-24} e cm, although its estimated value[1] (2.3×10^{-24} e cm) is somewhat higher than the experimental limits. In this paper, we apply Weinberg's idea to gauge models with right-handed charged currents, where the Higgs sector must already consist of a doublet and a triplet.[3] In order to have *CP* violation we now need only one additional doublet. Furthermore, we find that parity must be violated as well through the exchange of *neutral* Higgs bosons. (This also happens in the model of Ref. 1 and will contribute an extra term to the neutron electric dipole moment.) This new effect could be considerably bigger than that of the usual weak interaction in certain cases, and its detection in $\psi' \to \psi\pi\pi$ or $\psi' \to \psi\pi^0$ could serve as a test of the basic idea of *CP* nonconservation through Higgs exchange.

In Sec. II, the Higgs sector is analyzed and the nonconservation of *P* and *CP* explicitly shown. In Sec. III, we take the specific five-quark model of Ref. 3 and identify those processes in which *P* and *CP* are violated through Higgs exchange. The case $\sin\phi = 0$ (corresponding to a charm-conserving neutral current) is dealt with in detail. *CP* violation in $K_L \to 2\pi$ as well as the neutron electric dipole moment are determined by the same parameter which also leads naturally to large parity-violating effects in $\psi' \to \psi\pi\pi$ and $\psi' \to \psi\pi^0$. Finally in Sec. IV, we conclude with a summary and some remarks.

II. THE HIGGS SECTOR

In SU(2) × U(1) gauge models of weak and electromagnetic interactions with right-handed charged currents, two Higgs multiplets (one doublet and one triplet) are needed to make sure that all quarks have appropriate masses. The structure of this minimal Higgs sector has been fully analyzed in Ref. 3. However, if one more doublet is added then, in general, spontaneous breakdown of *P* and *CP* will occur. To show how this comes about explicitly, we write down the most general gauge-invariant, renormalizable Higgs potential for two doublets and one triplet

$$\begin{aligned} V = & -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \tfrac{1}{2}\mu_3^2\vec{\eta}\cdot\vec{\eta} + h_1(\Phi_1^\dagger\Phi_1)^2 + h_2(\Phi_2^\dagger\Phi_2)^2 + h_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + h_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + h_5(\Phi_1^\dagger\Phi_2)^2 + h_5^*(\Phi_2^\dagger\Phi_1)^2 + [h_6(\Phi_1^\dagger\Phi_2) + h_6^*(\Phi_2^\dagger\Phi_1)](\Phi_1^\dagger\Phi_1) + [h_7(\Phi_1^\dagger\Phi_2) + h_7^*(\Phi_2^\dagger\Phi_1)](\Phi_2^\dagger\Phi_2) \\ & + f_0(\vec{\eta}\cdot\vec{\eta})^2 + f_1(\Phi_1^\dagger\Phi_1)(\vec{\eta}\cdot\vec{\eta}) + f_2(\Phi_2^\dagger\Phi_2)(\vec{\eta}\cdot\vec{\eta}) + f_3(\Phi_1^\dagger\Phi_2)(\vec{\eta}\cdot\vec{\eta}) + f_3^*(\Phi_2^\dagger\Phi_1)(\vec{\eta}\cdot\vec{\eta}) \\ & + f_4(\Phi_1^\dagger\vec{\tau}\Phi_1)\cdot\vec{\eta} + f_5(\Phi_2^\dagger\vec{\tau}\Phi_2)\cdot\vec{\eta} + f_6(\Phi_1^\dagger\vec{\tau}\Phi_2)\cdot\vec{\eta} + f_6^*(\Phi_2^\dagger\vec{\tau}\Phi_1)\cdot\vec{\eta}, \end{aligned} \tag{2.1}$$

where $\Phi_1 = (\phi_1^+, \phi_1^0)$, $\Phi_2 = (\phi_2^+, \phi_2^0)$, and $\vec{\eta} = (\eta_1, \eta_2, \eta_3)$. Since h_5, h_6, h_7, f_3, f_6 need not be real, there are 22 independent parameters in V.

Let ϕ_1^0, ϕ_2^0, η^0 acquire vacuum expectation values $v_1/\sqrt{2}$, $v_2/\sqrt{2}$, $v_3/2$, respectively, and define

$$\phi_1^0 \equiv \frac{v_1}{\sqrt{2}}\left(1 + \frac{H_1 + i\chi_1}{|v_1|}\right), \quad \phi_2^0 \equiv \frac{v_2}{\sqrt{2}}\left(1 + \frac{H_2 + i\chi_2}{|v_2|}\right), \quad \eta^0 \equiv \frac{v_3}{2} + G, \tag{2.2}$$

where $|v_1|$, $|v_2|$, v_3, and the relative phase between v_1 and v_2 are determined by the condition that the shifted potential has no terms linear in the field. In the tree approximation, the four constraint equations are

$$-\mu_1^2|v_1|+h_1|v_1|^3+\tfrac{1}{2}(h_3+h_4)|v_1||v_2|^2+\mathrm{Re}h_5(v_1^*v_2)^2|v_1|^{-1} +\tfrac{3}{2}\mathrm{Re}(h_6v_1^*v_2)|v_1|+\tfrac{1}{2}\mathrm{Re}(h_7v_1^*v_2)|v_2|^2|v_1|^{-1}+\tfrac{1}{4}(f_1v_3-f_4)|v_1|v_3+\tfrac{1}{4}\mathrm{Re}(f_3v_3-f_6)v_1^*v_2v_3|v_1|^{-1}=0, \quad (2.3)$$

$$-\mu_2^2|v_2|+h_2|v_2|^3+\tfrac{1}{2}(h_3+h_4)|v_1|^2|v_2|+\mathrm{Re}h_5(v_1^*v_2)^2|v_2|^{-1} +\tfrac{3}{2}\mathrm{Re}(h_7v_1^*v_2)|v_2|+\tfrac{1}{2}\mathrm{Re}(h_6v_1^*v_2)|v_1|^2|v_2|^{-1}+\tfrac{1}{4}(f_2v_3-f_5)|v_2|v_3+\tfrac{1}{4}\mathrm{Re}(f_3v_3-f_6)v_1^*v_2v_3|v_2|^{-1}=0, \quad (2.4)$$

$$-\tfrac{1}{2}\mu_3^2v_3+\tfrac{1}{2}f_0v_3^3+\tfrac{1}{4}(2f_1v_3-f_4)|v_1|^2+\tfrac{1}{4}(2f_2v_3-f_5)|v_2|^2+\tfrac{1}{2}\mathrm{Re}(2f_3v_3-f_6)v_1^*v_2=0, \quad (2.5)$$

$$[\mathrm{Im}h_5(v_1^*v_2)^2+\tfrac{1}{2}\mathrm{Im}(h_6v_1^*v_2)|v_1|^2+\tfrac{1}{2}\mathrm{Im}(h_7v_1^*v_2)|v_2|^2+\tfrac{1}{4}\mathrm{Im}(f_3v_3-f_6)v_1^*v_2v_3]|v_1|^{-1}|v_2|^{-1}=0. \quad (2.6)$$

For charged states, the mass matrix is now given by

$$[-\mu_1^2+h_1|v_1|^2+\tfrac{1}{2}h_3|v_2|^2+\mathrm{Re}(h_6v_1^*v_2)+\tfrac{1}{4}(f_1v_3+f_4)v_3]\phi_1^-\phi_1^+ +[-\mu_2^2+h_2|v_2|^2+\tfrac{1}{2}h_3|v_1|^2+\mathrm{Re}(h_7v_1^*v_2)+\tfrac{1}{4}(f_2v_3+f_5)v_3]\phi_2^-\phi_2^+ +(-\mu_3^2+f_0v_3^2+f_1|v_1|^2+f_2|v_2|^2+2\,\mathrm{Re}f_3v_1^*v_2)\eta^-\eta^+ +[\tfrac{1}{2}h_4v_1v_2^*+h_5v_1^*v_2+\tfrac{1}{2}h_6|v_1|^2+\tfrac{1}{2}h_7|v_2|^2+\tfrac{1}{4}(f_3v_3+f_6)v_3]\phi_1^-\phi_2^++\mathrm{H.c.} +(\tfrac{1}{2}f_4v_1+\tfrac{1}{2}f_6v_2)\phi_1^-\eta^++\mathrm{H.c.}+(\tfrac{1}{2}f_5v_2+\tfrac{1}{2}f_6^*v_1)\phi_2^-\eta^++\mathrm{H.c.} \quad (2.7)$$

If the coefficient of any nondiagonal term such as $\phi_1^-\phi_2^+$ has an arbitrary phase, then CP is violated. Specifically, the coefficient of $\phi_1^-\phi_2^+/v_1^*v_2$ must have a nonzero imaginary part.[1] This is true in general for (2.7) since

$$\mathrm{Im}h_5(v_1^*v_2)^2+\tfrac{1}{2}\mathrm{Im}(h_6v_1^*v_2)|v_1|^2+\tfrac{1}{2}\mathrm{Im}(h_7v_1^*v_2)|v_2|^2+\tfrac{1}{4}\mathrm{Im}(f_3v_3+f_6)v_1^*v_2v_3=\tfrac{1}{2}\mathrm{Im}f_6v_1^*v_2v_3 \quad (2.8)$$

is not required to be zero. Notice that if $\vec{\eta}$ is absent, then f_3, f_6 are absent and by (2.6),

$$\mathrm{Im}h_5(v_1^*v_2)^2+\tfrac{1}{2}\mathrm{Im}h_6(v_1^*v_2)|v_1|^2+\tfrac{1}{2}\mathrm{Im}h_7(v_1^*v_2)|v_2|^2=0,$$

so there is no CP violation. Similarly, if either Φ_1 or Φ_2 is absent, then f_6 is absent in (2.7) and the same conclusion holds. (In Ref. 1, CP violation is achieved by using three or more doublets.) Let us define

$$A_1\equiv\tfrac{1}{2}f_5|v_2|^2v_3+\tfrac{1}{2}\mathrm{Re}f_6v_1^*v_2v_3,$$
$$A_2\equiv\tfrac{1}{2}f_4|v_1|^2v_3+\tfrac{1}{2}\mathrm{Re}f_6v_1^*v_2v_3,$$
$$A_3\equiv-\tfrac{1}{2}h_4|v_1|^2|v_2|^2-\mathrm{Re}h_5(v_1^*v_2)^2 -\tfrac{1}{2}\mathrm{Re}(h_6v_1^*v_2)|v_1|^2-\tfrac{1}{2}\mathrm{Re}(h_7v_1^*v_2)|v_2|^2 -\tfrac{1}{4}\mathrm{Re}(f_3v_3+f_6)v_1^*v_2v_3,$$
$$B\equiv\tfrac{1}{2}\mathrm{Im}f_6v_1^*v_2v_3;$$

then because of (2.3) to (2.6), the mass matrix (2.7) becomes

$$\frac{A_2+A_3}{|v_1|^2}\phi_1^-\phi_1^+-\frac{A_3-iB}{v_1^*v_2}\phi_1^-\phi_2^++\frac{A_2+iB}{v_1^*v_3}\phi_1^-\eta^+ -\frac{A_3+iB}{v_1v_2^*}\phi_2^-\phi_1^++\frac{A_1+A_3}{|v_2|^2}\phi_2^-\phi_2^++\frac{A_1-iB}{v_2^*v_3}\phi_2^-\eta^+ +\frac{A_2-iB}{v_1v_3}\eta^-\phi_1^++\frac{A_1+iB}{v_2v_3}\eta^-\phi_2^++\frac{A_1+A_2}{v_3^2}\eta^-\eta^+. \quad (2.10)$$

To extract the effect of CP violation due to the propagator $\langle\phi_1^-\phi_2^+\rangle$, we need to invert the above mass matrix. It can be shown that at zero momentun transfer,

$$\mathrm{Im}\frac{\langle\phi_1^-\phi_2^+\rangle}{v_1^*v_2}=-\frac{v_3^2}{v_0^2}\frac{B}{\Delta}, \quad (2.11)$$

$$\mathrm{Im}\frac{\langle\phi_1^-\eta^+\rangle}{v_1^*v_3}=-\frac{|v_2|^2}{v_0^2}\frac{B}{\Delta}, \quad (2.12)$$

$$\mathrm{Im}\frac{\langle\phi_2^-\eta^+\rangle}{v_2^*v_3}=\frac{|v_1|^2}{v_0^2}\frac{B}{\Delta}, \quad (2.13)$$

where $v_0^2=|v_1|^2+|v_2|^2+v_3^2$ and $\Delta=A_1A_2+A_2A_3+A_3A_1-B^2$. Details on how to obtain these exact results are given in the Appendix.

For the neutral states H_1, χ_1, H_2, χ_2, and G, we make the following important observation: Whereas the linear combination $(|v_1|^2+|v_2|^2)^{-1/2}(|v_1|\chi_1+|v_2|\chi_2)$ is absorbed by the neutral vector boson, the orthogonal state $(|v_1|^2+|v_2|^2)^{-1/2}(|v_2|\chi_1-|v_1|\chi_2)$ represents a bona fide physical degree of freedom and will in general mix with H_1, H_2, and G, thereby causing parity violation when coupled to fermions. For the Higgs potential (2.1), the mix mixing comes about mainly through the terms

$$[\mathrm{Im}h_5(v_1^*v_2)^2+\tfrac{1}{2}\,\mathrm{Im}(h_6v_1^*v_2)\,|v_1|^2+\tfrac{1}{2}\,\mathrm{Im}(h_7v_1^*v_2)\,|v_2|^2]\times\left(\frac{\chi_1}{|v_1|}-\frac{\chi_2}{|v_2|}\right)\left(\frac{H_1}{|v_1|}+\frac{H_2}{|v_2|}\right) \qquad (2.14)$$

and

$$\mathrm{Im}(f_3v_3-\tfrac{1}{2}f_6)v_1^*v_2\left(\frac{\chi_1}{|v_1|}-\frac{\chi_2}{|v_2|}\right)G. \qquad (2.15)$$

Therefore, if the parameter B in (2.9) and (2.11) to (2.13) is nonzero, then by (2.6), either (2.14) or (2.15) or both must be nonzero as well; i.e., *CP violation through charged Higgs exchange necessarily implies P violation through neutral Higgs exchange.* This ia also true for the model of Ref. 1, and as a result there is an additional contribution in that model to the neutron electric dipole moment which can be adjusted to fit the data. (Details are given in a separate paper.[4])

III. EFFECTS OF HIGGS EXCHANGE IN THE FIVE-QUARK MODEL

We choose the specific five-quark model of Ref. 3 because it is consistent with the present data on neutral currents as well as inclusive neutrino and antineutrino scattering.[3,5,6]

In this model, besides the usual left-handed doublets $(u,d_C)_L,(c,s_C)_L$, there is also a right-handed doublet $(u\cos\phi+c\sin\phi,b)_R$. We will discuss first the case $\sin\phi=0$, which corresponds to the model of Ref. 5. Modifications due to $\sin\phi\neq 0$ will be dealt with later.

We assume throughout that quarks and leptons are coupled to $\Phi_1=(\phi_1^+,\phi_1^0)$, $\tilde{\Phi}_2=(\bar{\phi}_2^0,-\phi_2^-)$, and $\vec{\eta}$, although $\tilde{\Phi}_2$ could be replaced by $\tilde{\Phi}_1$.[3] The quark-Higgs couplings are easily obtained from (3.13) of Ref. 3. The ones involving charged Higgs bosons are

$$\sqrt{2}\,(v_1^*)^{-1}\phi_1^-(m_s\sin\theta\,\bar{s}u_L+m_d\cos\theta\,\bar{d}u_L+m_b\bar{b}u_L+m_s\cos\theta\,\bar{s}c_L-m_d\sin\theta\,\bar{d}c_L)$$
$$+\sqrt{2}\,v_2^{-1}\phi_2^+(m_c\sin\theta\,\bar{c}d_L-m_c\cos\theta\,\bar{c}s_L)+\sqrt{2}\,v_3^{-1}\eta^+(m_u\cos\theta\,\bar{u}d_L+m_u\sin\theta\,\bar{u}s_L)+\sqrt{2}\,v_3^{-1}\eta^-(m_u\bar{b}u_L)+\mathrm{H.c.} \qquad (3.1)$$

For d-s transitions, *CP* violation occurs through the effective interaction

$$\frac{2\langle\phi_1^-\phi_2^+\rangle}{v_1^*v_2}m_sm_c\sin\theta\cos\theta\,\bar{s}c_L\bar{c}d_L+\frac{2\langle\phi_1^-\eta^+\rangle}{v_1^*v_3}m_sm_u\sin\theta\cos\theta\,\bar{s}u_L\bar{u}d_L\,, \qquad (3.2)$$

where m_d has been neglected versus m_s. Notice also that $\langle\phi_2^+\eta^-\rangle$ is not involved. Using (2.11) and (2.12), we now write down the effective *CP*-violating amplitude

$$-\frac{2B}{v_0^2\Delta}m_s\sin\theta\cos\theta(v_3^2m_c\bar{s}c_L\bar{c}d_L+|v_2|^2m_u\bar{s}u_L\bar{u}d_L)\,. \qquad (3.3)$$

The requirement of $I=\frac{1}{2}$ dominance[1] implies that

$$v_3^2m_c\gg|v_2|^2m_u\,. \qquad (3.4)$$

But v_3 is known to be very small compared to v_0 from neutral-current data,[3,7,8] so we must have

$$v_3\simeq|v_2|\ll|v_1|\simeq v_0\,. \qquad (3.5)$$

The parameter ImA of Ref. 1 is to be identified with $-2v_3^2B/v_0^2\Delta$ in (3.3); so as far as $\Delta S=1$, $\Delta C=0$ processes such as $K_L\to 2\pi$ are concerned, we have the same results. Notice that if $\tilde{\Phi}_2$ is replaced by $\tilde{\Phi}_1$ in (3.1), only the second term in (3.3) will survive, and there will be no $I=\frac{1}{2}$ dominance.

To obtain the neutron electric dipole moment, which is a $\Delta S=\Delta C=0$, *CP*-violating effect, we note that (3.1) would be identical to the corresponding expression of Ref. 1 if b were absent and $v_3^{-1}\eta^+$ replaced by $-(v_2)^{-1}\phi_2^+$. Accordingly, the electric dipole moments of the d and u quarks are given by[1]

$$D_d=\frac{em_d}{12\pi^2}\frac{B}{\Delta}\left(\frac{|v_2|^2}{v_0^2}m_u^2\cos^2\theta\ln\frac{m_H^2}{m_u^2}-\frac{v_3^2}{v_0^2}m_c^2\sin^2\theta\ln\frac{m_H^2}{m_c^2}\right),$$
$$D_u=-\frac{em_u}{24\pi^2}\frac{B}{\Delta}\frac{|v_2|^2}{v_0^2}\left(m_d^2\cos^2\theta\ln\frac{m_H^2}{m_d^2}+m_s^2\sin^2\theta\ln\frac{m_H^2}{m_s^2}\right), \qquad (3.6)$$

which would be the same as in Ref. 1 if $|v_2|^2$ were replaced by $-v_3^2$. But since $|v_2|^2\geq 0$, we have the following numerical bounds on D_d and D_u:

$$D_d\lesssim 0.77\times 10^{-24}\,e\,\mathrm{cm},\quad D_u\geq 0\,, \qquad (3.7)$$

assuming that $m_u\simeq m_d\simeq 0.3$ GeV, $m_s\simeq 0.5$ GeV, $m_c\simeq 1.5$ GeV, $m_H\simeq 15$ GeV, $\sin^2\theta\simeq 0.06$, and ImA $=-2v_3^2B/v_0^2\Delta\simeq 3.2\times 10^{-3}G_F/m_sm_c$ as in Ref. 1. Using the quark-model expression $(4D_d-D_u)/3$ for the neutron electric dipole moment D_n, we get

$$D_n\lesssim 1.0\times 10^{-24}\,e\,\mathrm{cm}\,. \qquad (3.8)$$

Furthermore, if $|v_2|^2=v_3^2$, then

$$D_n\simeq -0.2\times 10^{-24}\,e\,\mathrm{cm}\,. \qquad (3.9)$$

Both values are compatible with the most recent experimental result[9] of $(0.4\pm 1.1)\times 10^{-24}\,e$ cm. Notice that if (3.4) does not hold so that $|v_2|^2\gg v_3^2$, then D_n would be outside experimental limits.

So far, we have not considered the effect due to neutral Higgs exchange. However, it turns out that for our case it does not contribute significantly to D_n. To see this, we write down the analogous expression to (3.1) for neutral states:

$$|v_1|^{-1}H_1(m_d\bar{d}d+m_s\bar{s}s+m_b\bar{b}b)+|v_2|^{-1}H_2(m_c\bar{c}c)+v_3^{-1}G[m_u\bar{u}u-m_u\cos\theta(\bar{d}b_R+\bar{b}d_L)-m_u\sin\theta(\bar{s}b_R+\bar{b}s_L)]$$
$$+i|v_1|^{-1}\chi_1(m_d\bar{d}\gamma_5 d+m_s\bar{s}\gamma_5 s+m_b\bar{b}\gamma_5 b)-i|v_2|^{-1}\chi_2(m_c\bar{c}\gamma_5 c)\,. \quad (3.10)$$

Since $|v_1|^{-1} \ll |v_2|^{-1}, v_3^{-1}$, we need only consider χ_2 mixing with H_2 or G for parity-violating effects. However, these do not contribute to D_n. On the other hand, for the model of Ref. 1, a significant contribution does exist, and could in principle lower its calculated value of 2.3×10^{-24} e cm for D_n to within experimental limits. Details will be given elsewhere.

The largest effective parity-violating interaction from (3.10) is

$$-i\frac{\langle H_2\chi_2\rangle}{|v_2|^2}m_c^2(\bar{c}c)(\bar{c}\gamma_5 c)\,. \quad (3.11)$$

This contribution is not only enhanced by m_c^2 in the numerator, but also by the presence of $|v_2|^2\simeq v_3^2$, a small parameter, in the denominator. If m_H is the typical mass for a neutral Higgs boson, the strength of the coupling can be estimated to be $G_F(m_c^2/m_H^2)(v_0^2/|v_2|^2)$. For m_H about 5 GeV and $v_0/|v_2|\simeq10$, we have a factor-of-10 enhancement, although the effect could be much larger (see later discussion). An ideal situation for the observation of this effect is the Zweig-rule-suppressed decay $\psi'\to\psi\pi\pi$. This amplitude is approximately 10^{-1} to 10^{-2} times that of the usual strong interaction. Thus we anticipate a parity-violating effect of the order of one part in a hundred to a few parts in a thousand. The matrix element for the decay can be written as

$$\mathfrak{M}(\psi'(p)\to\psi(q)\pi(k_1)\pi(k_2))$$
$$=\epsilon'_\mu\epsilon_\nu[g^{\mu\nu}f_0+(k_1^\mu k_1^\nu+k_2^\mu k_2^\nu)f_1+(k_1^\mu k_2^\nu+k_2^\mu k_1^\nu)f_2+i\epsilon^{\mu\nu\lambda\sigma}p_\lambda(k_1+k_2)_\sigma f_3]\,. \quad (3.12)$$

The parity-violating part $f_3\simeq(10^{-2}$ to $10^{-3})\times f_1$. Determination of f_3 will require polarization measurements of ψ and ψ', but with the abundant occurrence of this decay, the experiment should be feasible.

We have suggested in Ref. 3 that the exchange of G can give rise to the $\Delta I=\frac{1}{2}$ rule in nonleptonic decays. In the limit $\sin\phi=0$ this effect can still be obtained if we require

$$\frac{m_u^2}{v_3^2}\frac{\langle GG\rangle}{G_F}\simeq4\,. \quad (3.13)$$

This in turn requires

$$\frac{m_c^2}{|v_2|^2}\frac{\langle H_2\chi_2\rangle}{G_F}\simeq100\,. \quad (3.14)$$

Thus retaining the $\Delta I=\frac{1}{2}$ rule through G exchange requires the parity-violating effect in $\psi'\to\psi\pi\pi$ to be further enhanced by a factor of about 10. Actually, a better process is $\psi'\to\psi\pi^0$. This is described in Ref. 10.

Because the charged Higgs bosons are responsible for CP-violating effects, they are expected to be quite massive, say, 15–20 GeV. However, the neutral Higgs bosons could have smaller masses. From (3.10) it is easy to see that G couples to $\bar{u}u$ and its strength can be estimated as

$$\frac{m_u}{v_0}\frac{v_0}{v_3}\simeq\frac{1}{750}\frac{v_0}{v_3}\simeq e/10\,. \quad (3.15)$$

Thus the production[3,11] of these bosons is suppressed by two orders of magnitude compared to an electromagnetic process and, once produced, their dominant decay is into charmed states through $G\to H_2\to\bar{c}c$.

So far, we have limited our discussion to the case $\sin\phi=0$. The presence of $\sin\phi$, however, will lead to a charm-changing neutral current, and gives rise to many interesting processes. We have discussed some of these in Ref. 3:

$$D^\pm\to\pi^\pm+\mu^++\mu^-\,,$$
$$D^0\to\mu^++\mu^-\,, \quad (3.16)$$
$$\bar{D}^0\to\mu^++\mu^-\,.$$

Note that $D^\pm\to K^\pm+\mu^++\mu^-$ are not allowed. A further test would be the reaction

$$\psi\to D+\pi\,. \quad (3.17)$$

This proceeds through Z exchange in our model, and could be of the same order as the Cabbibo-enhanced reaction $\psi\to D+K$. Zweig-rule suppression of the strong decays of ψ should make these reactions observable.

Our discussion of CP violation in $K_L\to\pi\pi$ is not altered significantly by the $\sin\phi$ terms. However, there is a new contribution to the electric dipole moment of the u quark from the neutral Higgs sector. The dominant contribution to the effective

Lagrangian is

$$i\frac{\langle\chi_2 G\rangle}{|v_2|v_3}m_u m_c\cos^2\phi\sin^2\phi\,\bar{u}c_R\bar{c}u_R\,. \tag{3.18}$$

The experimental limit on the neutron electric dipole moment leads to a constraint on the Higgs mass:

$$m_H > 20\cos\phi\sin\phi\frac{v_0}{v_3}\,\text{GeV}. \tag{3.19}$$

For $\sin\phi \simeq v_3/v_0$, we have $m_H > 20$ GeV. For larger values of $\sin\phi$, however, the neutral Higgs mass has to be even larger and the interesting parity-violating effect discussed earlier becomes unobservable.

Finally, since neutrinos are massless, only Φ_1 couples to leptons, and because $|v_1|^{-1}$ is assumed to be very small, lepton-Higgs couplings are negligible as in the standard model and lead to no observable effect.

IV. SUMMARY AND CONCLUSION

We have demonstrated the possibility of having P and CP nonconservation through the exchange of Higgs bosons in gauge models with right-handed charged currents. In the five-quark model,[3,5,6] we have shown the connection between the CP violation in $K_L \to 2\pi$ and the neutron electric dipole moment. The latter is derived from the former and found to be within experimental limits. Furthermore, we *predict* in the case $\sin\phi = 0$ (corresponding to a charm-conserving neutral current) that there is a large parity-violating effect in $\psi' \to \psi\pi\pi$ and $\psi' \to \psi\pi^0$. If $\sin\phi \neq 0$ (corresponding to a charm-changing neutral current) then this effect does not have to be so big; but in that case processes such as $\psi \to D\pi$ would be greatly enhanced. A detailed experimental investigation of the above can therefore tell us if CP nonconservation does occur through Higgs exchange and not by some other mechanism.

It is of course highly desirable that an actual Higgs boson be produced; but in our model the charged Higgs bosons are probably too heavy (15–20 GeV) to be seen in e^+e^- collisions, whereas the neutral ones with the exception of G have small couplings to ordinary matter. Because of this, it is even more important to look for parity violation in $\psi' \to \psi\pi\pi$ and $\psi' \to \psi\pi^0$. After all, this is the first process ever suggested that can *prove*, at least indirectly, the existence of Higgs particles. The theoretical impact of such a discovery would be strong indeed.

APPENDIX: GENERALIZED PROPAGATOR FOR HIGGS BOSONS

Since after spontaneous symmetry breakdown the mass matrix of the Higgs sector is no longer diagonal, it is useful to have a method of obtaining directly the propagator $\langle\phi_i^\dagger\phi_j\rangle$. Letting M_{ij} be a nonsingular Hermitian mass-squared matrix, then there exists a transformation Ω which diagonalizes M; i.e.,

$$\Omega M \Omega^{-1} = \lambda \tag{A1}$$

so that

$$M_{ij}a_j^{(n)} = \lambda^{(n)}a_i^{(n)}\,, \tag{A2}$$

where $\lambda^{(n)}$, $a^{(n)}$ are of course the eigenvalues and eigenstates of M, respectively. At zero momentum transfer, the propagator is given by

$$\langle\phi_i^\dagger\phi_j\rangle = \frac{\Omega^{-1}{}_{li}\Omega_{jk}}{-\lambda_{kl}} = -\Omega_{jk}\lambda^{-1}{}_{kl}\Omega^{-1}{}_{li} = -M^{-1}{}_{ji}\,, \tag{A3}$$

where the inverse mass-squared matrix M^{-1} can be evaluated by the usual method of cofactors.

But the Higgs mass-squared matrix will contain (at least) a zero-mass state s (corresponding to the longitudinal component of the appropriate vector boson), so M is in general singular. However, we can add the term $\lambda_0 s^* s$ to M, and then diagonalize the sum in the usual way. But in evaluating the propagator $\langle\phi_i^\dagger\phi_j\rangle$, we must subtract out the contribution due to s. The result, at zero momentum transfer, is

$$\langle\phi_i^\dagger\phi_j\rangle = -\lim_{\lambda_0\to 0}\frac{\text{cofactor}(M+\lambda_0)_{ij} - \text{cofactor}(M)_{ij}}{\det(M+\lambda_0)}\,. \tag{A4}$$

To obtain (2.11) to (2.13), we have used the above formula with

$$s^- = \frac{v_1\phi_1^- + v_2\phi_2^- - v_3\eta^-}{(|v_1|^2 + v_2|^2 + v_3^2)^{1/2}}\,. \tag{A5}$$

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