Properties of Higgs bosons in gauge models with right-handed charged currents*

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An SU(2) × U(1) gauge model of the weak and electromagnetic interactions with right-handed as well as left-handed charged currents must have, in general, four Higgs bosons: $Q^{\pm}$, H, and G. Not only are they in principle directly observable, their effects can also be indirectly felt in many ways just as with the intermediate vector bosons. In particular, they can contribute significantly to the weak nonleptonic decays of hadrons and might help to account for the $\Delta I = 1/2$ rule. We illustrate these ideas by considering in some detail a specific model which is consistent with the present data on neutral currents and inclusive neutrino and antineutrino data, and discuss both the production and the decay of these Higgs bosons. Based on the most recent e^+e^- data, we find that they must be heavier than about 1.7 GeV. Whereas the neutral Higgs bosons H and G are not easily produced, the charged ones $Q^{\pm}$ are expected to be found, say, in e^+e^- collisions. We discuss ways of ascertaining this.

I. INTRODUCTION

Many new SU(2)×U(1) gauge models of the weak and electromagnetic interactions have recently been proposed[1-6] which suggest that there are both left-handed and right-handed charged currents. Whereas a vectorlike[3-5] model is inconsistent with present neutral-current data, there is nevertheless strong evidence from antineutrino data at high energies for a right-handed charged current. We propose therefore to look at a specific gauge model which is consistent with all the present data, but our main concern is with the Higgs bosons which are naturally present in all such models with right-handed charged currents. Our discussion will be applicable to any other similar model with only slight modifications.

Although in theory elementary Higgs bosons are not absolutely necessary[7] for the construction of a unified gauge theory of the weak and electromagnetic interactions, it is still important to know whether or not they can be observed experimentally. This is especially true because the intermediate vector bosons are predicted to be so heavy they might be very hard to produce, while the Higgs bosons do not necessarily have to suffer the same fate. In the Weinberg-Salam model,[8] there is only one Higgs boson. However, it is electrically neutral and has only small couplings to leptons and hadrons. Ellis, Gaillard, and Nanopoulos[9] have studied its properties in detail and concluded that it is not very easy to observe, even if it has only a small mass. (A theoretical argument,[10] on the other hand, puts its mass above 3.72 GeV.) The situation is markedly different once right-handed charged currents are introduced. There are now four Higgs bosons: $Q^{\pm}$, H, and G. (This will be shown explicitly in Sec. III.) Being charged, $Q^{\pm}$ are easily produced electromagnetically, but they may not be easily identifiable as Higgs bosons. We will give a comprehensive discussion of this in Sec. IV.

In Sec. II we present our specific gauge model of the weak and electromagnetic interactions, which is consistent with present data on neutral currents and inclusive neutrino and antineutrino data, and observe that it has some very interesting new effects which can be directly tested experimentally. Our discussion in this section does not involve the Higgs bosons, and the model can be taken on its own. In Sec. III, details of the model with regard to the Higgs bosons are given. The part which deals with the Higgs interaction with the vector gauge bosons is common to all SU(2)×U(1) gauge models with right-handed charged currents. The rest is particular to our model, but all results can be easily generalized. In Sec. IV we discuss the production and the decay of $Q^{\pm}$, and similarly for H and G in Sec. V. We conclude from the most recent e^+e^- data that in our model $Q^{\pm}$, H, and G all have to be heavier than about 1.7 GeV. In Sec. VI, effects of the Higgs bosons on the weak nonleptonic decays of hadrons are discussed, with particular attention to the $\Delta I=\frac{1}{2}$ rule. In Sec. VII we make some concluding remarks.

II. THE MODEL

The model we are considering is the following simple extension of the four-quark version[11] of the Weinberg-Salam model:

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L, \begin{pmatrix} c \\ s_C \end{pmatrix}_L, \begin{pmatrix} u\cos\phi + c\sin\phi \\ b \end{pmatrix}_R \tag{2.1}$$

where d_C, s_C are the usual Cabibbo-rotated states and b is a new heavy quark. The subscripts L and R denote left-handed and right-handed, respectively. (This is in fact Model D of Ref. 2, but there it was not given much attention.)

The motivation for this model essentially comes from three recent corroborating pieces of data: (i) $d\sigma/dy$ for $\bar{\nu}N \to \mu^+ X$ shows a flat excess in y at high energies such that the charged-current ratio

$$\sigma(\bar{\nu}N \to \mu^+ X)/\sigma(\nu N \to \mu^- X)$$

rises to a value of around 0.7 above 50 GeV.[12] (ii) $d\sigma/dy$ for $\nu N \to \mu^- X$ is flat and $\sigma(\nu N \to \mu^- X)$ rises linearly with energy.[12] (iii) The neutral-current ratio $\sigma(\bar{\nu}N \to \bar{\nu}X)/\sigma(\nu N \to \nu X)$ is inconsistent[13] with the value of unity predicted by vectorlike[3-5] models. To explain (i) we need[14,15] the right-handed doublet as given, but to explain (ii) and (iii) we must also not have a similar right-handed doublet with a d quark.[16,17] The model of Ref. 17 is exactly our model with $\cos\phi = 1$, but there is at present insufficient experimental information to fix it at that value. On the contrary, present data favor a value of $\cos\phi$ of about 0.6.[18] This leads to some very interesting interrelated effects which can be (and will be) directly tested experimentally.

The charged current in this model is simply given by

$$J_\mu^\dagger = \bar{u}\gamma_\mu(1-\gamma_5)d_C + \bar{c}\gamma_\mu(1-\gamma_5)s_C + (\bar{u}\cos\phi + \bar{c}\sin\phi)\gamma_\mu(1+\gamma_5)b\ , \tag{2.2}$$

whereas the neutral current takes the form of

$$J_\mu^Z = \tfrac{1}{2}[\bar{u}\gamma_\mu(1-\gamma_5)u - \bar{d}\gamma_\mu(1-\gamma_5)d + \bar{c}\gamma_\mu(1-\gamma_5)c - \bar{s}\gamma_\mu(1-\gamma_5)s$$
$$+ (\bar{u}\cos\phi + \bar{c}\sin\phi)\gamma_\mu(1+\gamma_5)(u\cos\phi + c\sin\phi) - \bar{b}\gamma_\mu(1+\gamma_5)b\,]$$
$$- 2\sin^2\theta_W J_\mu^{\text{electromagnetic}}\ . \tag{2.3}$$

We note, however, that in this model, as in all models with right-handed charged currents, the neutral current is effectively enhanced because the mass of the neutral vector boson Z is reduced. (This is explained in Ref. 5, and will also be discussed here in Sec. III.) The extent of this enhancement is given in terms of a parameter we call $\cos\beta$ (κ in Ref. 5), whose experimental value turns out to be close to unity,[5] which is the value in the Weinberg-Salam model. As we shall see, this seemingly innocuous result has important consequences for the phenomenology of Higgs bosons.

Under the assumptions of a quark-parton model, the neutral-to-charged-current ratios for neutrino and antineutrino inclusive cross sections are calculated to be

$$R_\nu \equiv \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^- X)} = (\tfrac{1}{2} - \sin^2\theta_W + \tfrac{20}{27}\sin^4\theta_W) + \frac{\cos^2\phi}{12}\left(1 - \frac{8\sin^2\theta_W}{3}\right) \tag{2.4}$$

and

$$R_{\bar{\nu}} \equiv \frac{\sigma(\bar{\nu}N \to \bar{\nu}X)}{\sigma(\bar{\nu}N \to \mu^+ X)} = (\tfrac{1}{2} - \sin^2\theta_W + \tfrac{20}{9}\sin^4\theta_W) + \frac{3\cos^2\phi}{4}\left(1 - \frac{8\sin^2\theta_W}{3}\right) \tag{2.5}$$

below b threshold.

Furthermore, the charged-current ratio of antineutrino to neutrino inclusive cross sections is given by

$$\frac{\sigma(\bar{\nu}N \to \mu^+ X)}{\sigma(\nu N \to \mu^- X)} = \begin{cases} \tfrac{1}{3} & \text{below } b \text{ threshold} \\ \tfrac{1}{3} + \cos^2\phi & \text{well above } b \text{ threshold.} \end{cases} \tag{2.6}$$

The neutral-current ratio below b threshold is therefore

$$\frac{\sigma(\bar{\nu}N \to \bar{\nu}X)}{\sigma(\nu N \to \nu X)} = \frac{[R_{\bar{\nu}}]_{\text{below } b \text{ threshold}}}{3R_\nu}\ . \tag{2.7}$$

Also, in the above, N denotes an average nucleon target, and we consider the effects of only the valance quarks.

The experimental values for the above quantities from the Harvard-Pennsylvania-Wisconsin-Fermilab collaboration are[12,13]

$$R_\nu = 0.29 \pm 0.04\ ,$$
$$0.25 \pm 0.07 \le R_{\bar{\nu}} \le 0.39 \pm 0.10\ ,$$
$$\frac{\sigma(\bar{\nu}N \to \mu^+ X)}{\sigma(\nu N \to \mu^- X)} \simeq 0.7 \quad \text{for } E > 50 \text{ GeV}\ , \tag{2.8}$$
$$\frac{\sigma(\bar{\nu}N \to \bar{\nu}X)}{\sigma(\nu N \to \nu X)} \le 0.68 \pm 0.17\ .$$

These values are also consistent with data from CERN[19] and from the Caltech-Fermilab collaboration.[20] A good fit to the data is then given by[18]

$$\cos\phi \simeq 0.6 , \qquad (2.9)$$

and

$$\sin^2\theta_W \simeq 0.3 .$$

Using these values, we obtain

$$R_\nu = 0.27 ,$$
$$R_{\bar\nu} = 0.45 , \qquad (2.10)$$

and

$$\frac{\sigma(\bar\nu N \to \bar\nu X)}{\sigma(\nu N \to \nu X)} = 0.56 ,$$

in excellent agreement with the data. (Although any value of $\cos\phi \gtrsim 0.6$ is allowed, the neutral-current ratio favors $\cos\phi \simeq 0.6$. Details are given in Ref. 18.) To find out if $\cos\phi$ has indeed this value we can wait for further experimental measurements of the charged-current ratio at still higher energies, or we can look at the effects of the neutral current in (2.3), which has a $|\Delta C| = 1$ piece. (C denotes charm,[21] as discussed in detail by Gaillard, Lee and Rosner,[22] whose notation we will follow in this paper.) For example, we have the following semileptonic decay amplitudes which would be highly suppressed in the standard four-quark Weinberg-Salam model:

$$\mathfrak{M}(D^0 \to \mu^+\mu^-) = \sin\phi\cos\phi G_F f_D m_\mu \bar u_\mu v_\mu , \qquad (2.11)$$

where f_D is a constant analogous to f_π involved in the decay $\pi^+ \to \mu^+\nu$, and

$$\mathfrak{M}(D^+ \to \pi^+ e^+ e^-)$$
$$= \sin\phi\cos\phi \frac{G_F}{\sqrt 2} p_D^\mu \bar u_e \gamma_\mu \{1 - 4\sin^2\theta_W - \gamma_5\} v_e . \qquad (2.12)$$

They are comparable in magnitude to the usual charged-current decays such as $D^+ \to \mu^+\nu$ and $D^0 \to K^- e^+\nu$, and should be observable if present. Furthermore, they should contribute to the ratio of trimuon versus dimuon events now being observed in muon deep-inelastic experiments.[23] We write down some matrix elements for the charged-current modes (which are the same as in the Weinberg-Salam model), for comparison:

$$\begin{aligned}
\mathfrak{M}(D^+ \to \mu^+\nu) &= iG_F \sin\theta f_D m_\mu \bar u_\mu (1-\gamma_5) v_\nu , \\
\mathfrak{M}(D^0 \to \pi^- e^+\nu) &= G_F \sin\theta p_D^\mu \bar u_e \gamma_\mu (1-\gamma_5) v_\nu , \\
\mathfrak{M}(F^+ \to \mu^+\nu) &= iG_F \cos\theta f_F m_\mu \bar u_\mu (1-\gamma_5) v_\nu , \\
\mathfrak{M}(D^0 \to K^- e^+\nu) &= G_F \cos\theta p_D^\mu \bar u_e \gamma_\mu (1-\gamma_5) v_\nu .
\end{aligned} \qquad (2.13)$$

Another important consequence of the $|\Delta C| = 1$ neutral current is the K/π ratio for charmed-particle decay. We recall that the standard model predicts that $|\Delta C| = 1$, $\Delta S = 0$ decays are suppressed by $\sin^2\theta_C$ relative to $|\Delta C| = 1$, $\Delta S = \Delta C$ decays. In this model, however, the $|\Delta C| = 1$ neutral current makes the former rate much larger and it is not necessary for the K/π ratio in e^+e^- annihilation to show a rise. We should add that a new charged-current transition ($c \to b \to u$) is also involved in boosting $|\Delta C| = 1$, $\Delta S = 0$ decays.

To conclude this section we wish to point out that although this model has a rich variety of consequences, they all stem from one single parameter: $\cos\phi$. It should therefore be easy either to confirm or to refute, once experimental information becomes available. The remaining sections of this paper will be concerned with the properties of the Higgs bosons in a gauge model of this type. However, we will use this specific model to illustrate our ideas.

III. THE HIGGS SECTOR

To make sure that all particles in the gauge model acquire mass, we need two Higgs multiplets. (The necessity of this will be explicitly demonstrated.) Let

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \text{ and } \vec\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \\ \eta^- \end{pmatrix} ; \qquad (3.1)$$

then the most general renormalizable interaction potential is

$$V = h_1(\Phi^\dagger\Phi)^2 - \mu_1^2(\Phi^\dagger\Phi) + h_2(\vec\eta\cdot\vec\eta)^2 - \tfrac12\mu_2^2(\vec\eta\cdot\vec\eta) + f_1(\Phi^\dagger\Phi)(\vec\eta\cdot\vec\eta) + f_2(\Phi^\dagger\vec\tau\Phi)\cdot\vec\eta . \qquad (3.2)$$

Spontaneous symmetry breakdown occurs when the minimum of the potential is at

$$\langle\phi^0\rangle = \frac{v_1}{\sqrt2} \text{ and } \langle\eta^0\rangle = \frac{v_2}{2} , \qquad (3.3)$$

where v_1 and v_2 are related to the coupling constants by

$$4(h_1 v_1^2 - \mu_1^2) + f_1 v_2^2 - f_2 v_2 = 0 \qquad (3.4)$$

and

$$2(h_2 v_2^2 - \mu_2^2) + 2 f_1 v_1^2 - f_2 \frac{v_1^2}{v_2} = 0 . \qquad (3.5)$$

The states of interest are now

$$\begin{aligned}
G &= \eta^0 - \langle\eta^0\rangle , \\
H &= \sqrt2\,\mathrm{Re}(\phi^0 - \langle\phi^0\rangle , \\
\chi &= \sqrt2\,\mathrm{Im}\phi^0 , \\
s^\pm &= \cos\beta\,\phi^\pm - \sin\beta\,\eta^\pm , \\
Q^\pm &= \sin\beta\,\phi^\pm + \cos\beta\,\eta^\pm ,
\end{aligned} \qquad (3.6)$$

where $\tan\beta = v_2/v_1$. As is well known, the states $s^\pm$ and χ are would-be Goldstone bosons which become the longitudinal components of the intermediate vector bosons $W^\pm$ and Z, and disappear from the physical spectrum.[24] However, the remaining states $Q^\pm$, H, and G are physical, and their properties are what we will be concerned with. We note that the states H and G are in general mixed. The condition for no mixing is

$$2f_1 v_2 = f_2 . \tag{3.7}$$

We assume this for simplicity in our subsequent discussion. Our results are, of course, easily modifiable to accommodate this mixing.

Masses of the vector gauge bosons in this model are given by

$$M_W = \frac{e(v_1^2 + v_2^2)^{1/2}}{2\sin\theta_W} ,$$
$$M_Z = \frac{M_W}{\cos\theta_W}\cos\beta , \tag{3.8}$$

where e is the electromagnetic coupling constant and θ_W is the Weinberg angle. The effective strength of the neutral current is enhanced because M_Z is reduced by $\cos\beta$, which of course is equal to unity in the Weinberg-Salam model. This parameter $\cos\beta$ is called κ in Ref. 5, where it is found that, to be consistent with data, we must have

$$\cos\beta \gtrsim 0.9 . \tag{3.9}$$

Following Ref. 24, we write down the Lagrangian for the interaction of the Higgs bosons with the vector gauge bosons:

$$\begin{aligned}\mathcal{L}_{\text{int}} = & \left| \partial_\mu \phi^+ + iM_W \cos\beta W_\mu^+ + \frac{ig}{2} W_\mu^+ (H + i\chi) + i\left[-eA_\mu + \frac{g\cos(2\theta_W)}{2\cos\theta_W} Z_\mu\right]\phi^+ \right|^2 \\ & + \left| \partial_\mu \eta^+ - iM_W \sin\beta\, W_\mu^+ - igW_\mu^+ G + i[-eA_\mu + g\cos\theta_W Z_\mu]\eta^+ \right|^2 \\ & + \frac{1}{2}\left| \partial_\mu (H + i\chi) - M_Z Z_\mu - \frac{ig}{2\cos\theta_W} Z_\mu (H + i\chi) + igW_\mu^- \phi^+ \right|^2 \\ & + \tfrac{1}{2}\left| \partial_\mu G - igW_\mu^- \eta^+ + igW_\mu^+ \eta^- \right|^2 ,\end{aligned} \tag{3.10}$$

where $e = -g\sin\theta_W$, and the Fermi weak coupling constant is given by

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} . \tag{3.11}$$

The various scalar-vector couplings are then easily obtained by inspection of (3.10).

Taking the masses of the Higgs bosons as independent parameters, we reexpress the couplings in (3.2) in a more useful form:

$$\begin{aligned} & h_1 = \frac{g^2}{8\cos^2\beta}\frac{m_H^2}{M_W^2} , \quad h_2 = \frac{g^2}{8\sin^2\beta}\frac{m_G^2 - m_Q^2\cos^2\beta}{M_W^2} , \\ & f_1 = \frac{g^2}{4}\frac{m_Q^2}{M_W^2} , \quad f_2 = g\sin\beta\,\frac{m_Q^2}{M_W} . \end{aligned} \tag{3.12}$$

It is therefore easily seen that if Higgs bosons are extremely heavy, they must also interact strongly among themselves. This is in fact the situation in vectorlike[3-5] models, where G contributes directly[5] to the K_L-K_S mass difference and must therefore be extremely heavy ($\sim 10^3$ GeV). In our model, this is not the case, and it is perfectly consistent to deal with Higgs bosons with masses of the order of a few GeV. (If the theoretical argument of Weinberg[10] is used, moderate lower bounds on these masses can presumably be obtained.)

Our discussion so far concerns only the scalar-scalar and the scalar-vector interactions and is therefore completely general. However, the scalar-spinor interactions are model-dependent. For our model, they are given by

$$-\mathcal{L}_{\rm int}=\frac{g}{\sqrt{2}}\frac{m_d}{M_W\cos\beta}(\bar{u}_C,\bar{d})d_R\Phi+\frac{g}{\sqrt{2}}\frac{m_s}{M_W\cos\beta}(\bar{c}_C,\bar{s})s_R\Phi+\frac{g}{\sqrt{2}}\frac{m_b}{M_W\cos\beta}(\bar{u}\cos\phi+\bar{c}\sin\phi,\bar{b})b_R\Phi$$
$$+\tfrac{1}{2}m_u\cos\phi[\bar{u}(u\cos\phi+c\sin\phi)_R+\bar{d}_C b_R]+\frac{g\,m_u\cos\phi}{2\,M_W\sin\beta}(\bar{u},\bar{d}_C)\begin{bmatrix}\eta^0 & \sqrt{2}\eta^+\\ \sqrt{2}\eta^- & -\eta^0\end{bmatrix}\begin{bmatrix}u\cos\phi+c\sin\phi\\ b\end{bmatrix}_R$$
$$-\frac{g}{\sqrt{2}}\frac{m_u\sin\phi}{M_W\cos\beta}(\bar{u},\bar{d}_C)(c\cos\phi-u\sin\phi)_R\tilde{\Phi}+\tfrac{1}{2}m_c\sin\phi[\bar{c}(u\cos\phi+c\sin\phi)_R+\bar{s}_C b_R]$$
$$+\frac{g}{2}\frac{m_c\sin\phi}{M_W\sin\beta}(\bar{c},\bar{s}_C)\begin{bmatrix}\eta^0 & \sqrt{2}\eta^+\\ \sqrt{2}\eta^- & -\eta^0\end{bmatrix}\begin{bmatrix}u\cos\phi+c\sin\phi\\ b\end{bmatrix}_R+\frac{g}{\sqrt{2}}\frac{m_c\cos\phi}{M_W\cos\beta}(\bar{c},\bar{s}_C)(c\cos\phi-u\sin\phi)_R\tilde{\Phi}$$
$$+\text{Hermitian conjugate terms}\,, \tag{3.13}$$

where $u_C=u\cos\theta_C-c\sin\theta_C$, $c_C=c\cos\theta_C+u\sin\theta_C$, and $\tilde{\Phi}=(\bar{\phi}^0,-\phi^-)$. From the above explicit expression it can be seen that if the triplet Higgs bosons were absent, $m_u=m_c=0$.

The leptonic sector is taken to be that of Weinberg-Salam model, with the possible addition of a right-handed doublet as in Ref. 17. This new lepton doublet can be used to explain the anomalous $e\mu$ events observed[25] in e^+e^- annihilation, and its conjectured right-handed character will ensure the absence of triangle anomalies in our model. But since this right-handed lepton doublet does not have a member in common with the left-handed lepton doublets, they are not coupled to the triplet Higgs bosons. As we shall see, this effectively suppresses $Q^\pm$ production by neutrinos.

In the following sections, we will deal with the properties of $Q^\pm$, H, and G in some detail. To obtain definite results, we will often use the scalar-quark couplings of (3.13). In Sec. VI, some use will be made of the scalar-vector couplings of (3.10) as well as trilinear scalar couplings derivable from (3.2).

IV. PROPERTIES OF $Q^\pm$

The charged Higgs bosons are much easier to produce than their neutral counterparts because of their coupling to the electromagnetic field. Their couplings to quark fields are given in (3.13). Keeping only the largest contributions, we find

$$\mathcal{L}_{\rm int}=\frac{g\cot\beta}{\sqrt{2}M_W}Q^+[m_c\cos\theta\sin\phi(\cos\phi\bar{u}s_L+\sin\phi\bar{c}s_L)+(m_u\cos\theta\cos\phi-m_c\sin\theta\sin\phi)(\cos\phi\bar{u}d_L+\sin\phi\bar{c}d_L)$$
$$+\cos\phi(m_u\bar{u}b_R-m_b\tan^2\beta\,\bar{u}b_L)+\sin\phi(m_c\bar{c}b_R-m_b\tan^2\beta\,\bar{c}b_L)]$$
$$+\text{Hermitian conjugate.} \tag{4.1}$$

In the above, we have neglected $\sin\theta$ relative to $\cos\theta$, $\sin\beta$ relative to $\cos\beta$, and m_u, m_d, m_s relative to m_c and m_b.

Inspection of the coupling shows that if the mass of $Q^\pm$ were small enough, hadronic decays into $Q^\pm$ states would be several orders of magnitude larger than the usual nonleptonic decays. For example,

$$\frac{\Gamma(K^0\to Q^+\pi^-)}{\Gamma(K^0\to\pi^+\pi^-)}\simeq 10^7\,. \tag{4.2}$$

We can thus rule out a mass of Q less than (m_K-m_π). For a similar reason, the recent observation of a $K^\pm\pi^\mp$ resonance at 1.86 GeV,[26] presumably the state D^0 or $\bar{D}^0$, definitely rules out the mass range below 1.7 GeV, since the two-body branching ratio would otherwise be vanishingly small.

The easiest way to produce $Q^\pm$ is in pair production in e^+e^- colliding-beam experiments. The production cross section is given by

$$\frac{\sigma(e^+e^-\to Q^+Q^-)}{\sigma(e^+e^-\to\mu^+\mu^-)}=\frac{1}{4}\left(\frac{s-4m_Q{}^2}{s}\right)^{3/2}. \tag{4.3}$$

The subsequent decay can be observed through

$$Q^+\to D^0K^+,\quad D^0\to K^-\pi^+ \tag{4.4}$$

or

$$Q^+\to K^0\pi^+,\quad K^0\to\pi^+\pi^-\,.$$

The large production cross section and the narrow width visible in charged-meson final states should make it not too difficult to observe. We expect the lifetime of these states to be approximately 10^{-15} seconds. Q^+ prefers to decay into states with total strangeness 1 whereas the charmed meson F^+ decays substantially into states with total strangeness 0,[27] so they would not be confused with each other even at nearly the same mass. They also have greatly different lifetimes, but these may be very hard to measure experimentally.

An alternate way of producing $Q^\pm$ is through neutrino beams on a proton target. The mechanism is similar to $W^\pm$ production, involving one semiweak vertex and a photon exchange. However, this process is suppressed by a factor of $\tan^2\beta$ because leptons do not couple to the triplet Higgs bosons. The production cross section of Q^+ can be calculated from Ref. 28, where a similar boson mediates weak interactions. For $E_\nu \simeq 100$ GeV, and $m_Q \simeq 2$ GeV, we find

$$\sigma(\nu p \to \mu^- Q^+ p) = \tan^2\beta \times 1.042 \times 10^{-39}\ \text{cm}^2. \quad (4.5)$$

This is smaller than the deep-inelastic scattering cross section by a factor of $\tan^2\beta/600$. Furthermore, the subsequent decay of Q^+ into leptons versus hadrons is also suppressed by a factor of $\tan^4\beta$. Dimuon events seen[29] in neutrino experiments cannot be explained by the production of a new particle at the lepton vertex in any case.[30] We should also note that the amplitude ratio $Q^+ \to \mu^+\nu/Q^+ \to e^+\nu$ is equal to m_μ/m_e, so that $Q^\pm$ cannot account for the anomalous $e\mu$ events seen[25] in e^+e^- annihilation.

V. PROPERTIES OF H AND G

Couplings of H and G to quarks are also contained in (3.13). Explicitly they are given by

$$\begin{aligned} -\mathcal{L}_{\text{int}} = \frac{gH}{2M_W\cos\beta}&[m_d\bar{d}d + m_s\bar{s}s + m_b\bar{b}b + m_u\sin^2\phi\,\bar{u}u \\ &+ m_c\cos^2\phi\,\bar{c}c - \sin\phi\cos\phi(m_u\bar{u}c_R + m_c\bar{u}c_L + \text{H.c.})] \\ + \frac{gG}{2M_W\sin\beta}&[m_u\cos^2\phi\,\bar{u}u + m_c\sin^2\phi\,\bar{c}c + \sin\phi\cos\phi(m_u\bar{u}c_R + m_c\bar{u}c_L + \text{H.c.}) \\ &- (m_u\cos\theta\cos\phi - m_c\sin\theta\sin\phi)(\bar{b}d_L + \text{H.c.}) - (m_u\sin\theta\cos\phi + m_c\cos\theta\sin\phi)(\bar{b}s_L + \text{H.c.})]. \end{aligned} \quad (5.1)$$

The production and decay of H are therefore very similar to those of its counterpart in the Weinberg-Salam model, as discussed in detail in Ref. 9. However, there is one important distinction. In our model, $|\Delta C| = 1$ transitions are possible. If kinematically allowed, charmed hadrons would decay predominantly into H plus other hadrons, because this interaction is only semiweak whereas usual charmed-particle decay is weak. (This is of course the same argument as used for $Q^\pm$ in the previous section.) For example,

$$\frac{\Gamma(D^+ \to H\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} \simeq 10^7. \quad (5.2)$$

The observation[26] of $D^0 \to K^-\pi^+$ at the level of a few percent of its total rate can therefore also rule out the possibility that $m_H < m_D - m_\pi$. Obviously, this result also holds for G. Furthermore, if H or G were produced, they would decay into $\pi^-\pi^+$ or K^-K^+ and be observed. We note that H or G cannot decay into $K^\pm\pi^\mp$ in our model; thus the observed resonance is not H or G. We conclude therefore that

$$m_H, m_G \gtrsim 1.7\ \text{GeV}. \quad (5.3)$$

Since H and G do not seem to be observed in charmed-particle decay, their direct experimental detectability is in the same sorry state as determined by Ref. 9 (although G could be a decay product of hadrons involving the b quark). However, they might serve a very useful purpose for our understanding of weak nonleptonic decays of hadrons, to be discussed in the next section.

VI. HIGGS CONTRIBUTION TO NONLEPTONIC DECAYS

In Sec. II, we remarked that in our model the neutral vector boson Z contributes sufficiently to the weak nonleptonic decays of charmed hadrons that the K/π ratio does not need to show a rise. Similarly, the Higgs bosons can play the same role. We first consider $|\Delta S| = 1$ transitions such as $K \to 2\pi$. The relevant diagrams are shown in Fig. 1. The contributions of diagrams 1(a) and 1(b) are comparable, and the part which is due to $Q^\pm$ is roughly equal to $\frac{1}{4}(m_c^2/m_Q^2)\sin^2\phi\cos^2\phi\cot^2\beta$ times that of the $W^\pm$. In Ref. 1, because of the particular choice of right-handed charged current, diagram 1(b) dominates over 1(a) to give the $\Delta I = \frac{1}{2}$ rule. In our case, we must look to diagram 1(c), which is about $\frac{1}{2}(m_Q^2/m_b^2)(1/\sin^2\phi\cos^2\beta)$ times 1(b). To get the $\Delta I = \frac{1}{2}$ rule, assuming $m_c \simeq 1.5$ GeV, m_G

$\lesssim m_b \simeq 4$ GeV,[14] and $\cos\phi \simeq 0.6$, we must have $\sin\beta \ll 0.08$ and $m_Q \gg 4.5$ GeV. Since diagrams 1(b) and 1(c) contain mass and wave-function renormalization contributions which must be removed before direct comparison with 1(a) can be made, we follow the argument of Ref. 5 in obtaining the above numbers. The vacuum contribution to the K_L-K_S mass difference will be large whenever the $\Delta I = \frac{1}{2}$ rule is achieved in this fashion,[5] but this in itself may not be too serious a problem, as other intermediate states can contribute.[5,6] We forego an exact calculation of this in our model for that reason. The important point to be made here is that the $\Delta I = \frac{1}{2}$ rule can come about through Higgs bosons as well as through vector gauge bosons. In our model, such a rule is not "built in" as in Ref. 1, but is rather a consequence under certain conditions.

We now consider $|\Delta C| = 1, \Delta S = 0$ nonleptonic decays. In addition to the contributions from the vector gauge bosons discussed in Sec. II, we find an important diagram involving the Higgs boson G [Fig. 2(a)]. It is roughly equal to $\frac{1}{8}(m_c^2/m_G^2) \times (\sin^3\phi \cos\phi/\sin^2\beta)$ times that of the $W^\pm$ contribution. For the parameters given in the previous paragraph to get the $\Delta I = \frac{1}{2}$ rule, this factor is much bigger than unity. [Other diagrams, such as Fig. 2(b), have much smaller contributions.] This implies that $|\Delta C| = 1, \Delta S = 0$ decays are actually enhanced relative to $|\Delta C| = 1, \Delta S = \Delta C$ decays. (As noted in Ref. 5, however, it is very difficult theoretically to get exact numerical results for actual nonleptonic decays.) This can be tested experimentally.

We find therefore that in our model both the $\Delta I = \frac{1}{2}$ rule and the K/π ratio in charmed-particle decays can be understood through Higgs bosons, and they are intimately related. No attempt was made to build in these features as in Ref. 1. They are simply consequences of putting in a right-handed charged current to explain antineutrino data at very high energies. It is satisfying to see how a gauge model with Higgs bosons can correlate phenomena in such greatly different energy régimes.

VII. CONCLUSION

We have presented in this paper a discussion of the importance of Higgs bosons in gauge models. They should not be considered as silent partners in a world dominated by the vector gauge bosons, especially when right-handed charged currents are present. On the contrary, they may very well be important in their own right. Unfortunately, of the four Higgs bosons $Q^\pm$, H, and G, only $Q^\pm$ are likely to be produced at all. Needless to say, experimental confirmation of this would be very important indeed. But even if they are not detected at present energies, their theoretical implications are still many. We have shown in Sec. VI how in a simple model certain effects can arise through the Higgs bosons only. In fact, as we progressed through this work, we were pleasantly surprised

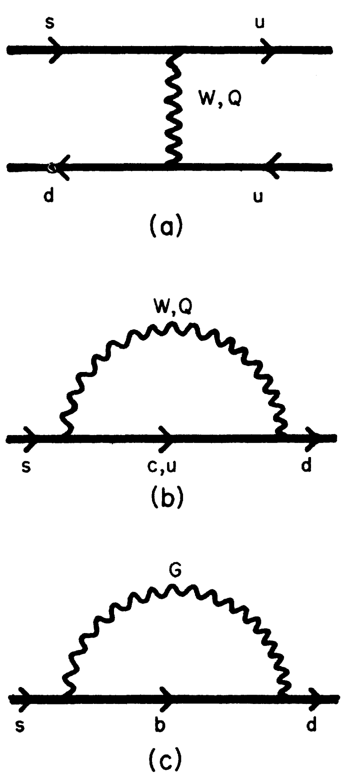

FIG. 1. Diagrams for nonleptonic $|\Delta S| = 1$ transitions.

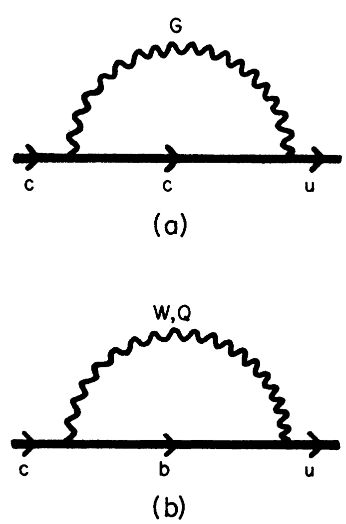

FIG. 2. Diagrams for nonleptonic $|\Delta C| = 1$, $\Delta S = 0$ transitions.

at the rich variety of interesting new interrelated phenomena that came out of the simple model we had written down only for illustration purposes. Experimental measurements of the parameters $\cos\beta$ and $\cos\phi$ would determine whether or not some of our specific ideas are correct, but the clincher would be the discovery of $Q^{\pm}$ whose properties are essentially dependent only upon their vector companions $W^{\pm}$, as discussed in Sec. III and Sec. IV. Although the production properties of $Q^{\pm}$ by e^+e^- annihilation are model-independent, the subsequent decay of $Q^{\pm}$ is not and there is no unambiguous experimental signal for it. In principle, Higgs-particle decays are semiweak and so are much stronger than ordinary weak decays of hadrons, but unfortunately, because of the large phase space involved, neither decay leaves a discernible track for experimental study. Although it is likely that our specific model may not be able to stand the test of time, our general discussion of the properties of the Higgs bosons in gauge models with right-handed charged currents will be useful both as an experimental guideline and as a theoretical tool for future model building.

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[1]A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 35, 69 (1975).

[2]F. A. Wilczek, A. Zee, R. L. Kingsley, and S. B. Treiman, Phys. Rev. D 12, 2768 (1975).

[3]S. Pakvasa, W. A. Simmons, and S. F. Tuan, Phys. Rev. Lett. 35, 702 (1975).

[4]H. Fritzsch, M. Gell-Mann, and P. Minkowski, Phys. Lett. 59B, 256 (1975).

[5]A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. D 12, 3589 (1975).

[6]G. Branco, T. Hagiwara, and R. N. Mohapatra, Phys. Rev. D 13, 104 (1976).

[7]S. Weinberg, Phys. Rev. D 13, 974 (1976).

[8]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity* (*Nobel Symposium No. 8*), edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

[9]J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B106, 292 (1976).

[10]S. Weinberg, Phys. Rev. Lett. 36, 294 (1976).

[11]S. Weinberg, Phys. Rev. D 5, 1412 (1972).

[12]A. Benvenuti *et al.*, Phys. Rev. Lett. 36, 1478 (1976); 37, 189 (1976).

[13]P. Wanderer, in *Proceedings of the International Conference on the Production of Particles with New Quantum Numbers*, edited by D. B. Cline and J. J. Kolonko (Univ. of Wisconsin, Madison, 1976), p. 404.

[14]R. M. Barnett, Phys. Rev. Lett. 36, 1163 (1976).

[15]S. Pakvasa, L. Pilachowski, W. A. Simmons, and S. F. Tuan, Nucl. Phys. B109, 469 (1976).

[16]G. J. Aubrecht II, E. Takasugi, and K. Tanaka, Phys. Rev. D 13, 1877 (1976).

[17]V. Barger and D. V. Nanopoulos, Phys. Lett. 63B, 168 (1976); see also Y. Achiman, K. Koller, and T. F. Walsh, *ibid.* 59B, 261 (1975).

[18]K. P. Das and N. G. Deshpande, Phys. Rev. D 15, (to be published).

[19]V. Brisson, report at Rencontre de Moriond, Flaine, 1976 (unpublished).

[20]L. Stutte, in *Proceedings of the International Conference on the Production of Particles with New Quantum Numbers*, edited by D. B. Cline and J. J. Kolonko (Univ. of Wisconsin, Madison, 1976), p. 388.

[21]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[22]M. K. Gaillard, B. W. Lee, and J. J. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[23]K. W. Chen, in *Proceedings of the International Conference on the Production of Particles with New Quantum Numbers*, edited by D. B. Cline and J. J. Kolonko (Univ. of Wisconsin, Madison, 1976), p. 222.

[24]K. Fujikawa, B. W. Lee, and A. I. Sanda, Phys. Rev. D 6, 2923 (1972).

[25]M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[26]G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 255 (1976).

[27]R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee, Phys. Rev. D 11, 1919 (1975).

[28]P. C. McNamee, Phys. Rev. D 9, 275 (1974).

[29]A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1199 (1975); 35, 1203 (1975); 35, 1249 (1975).

[30]The signature for such a production is a fast μ^+ in neutrino experiments. This is not observed. See Ref. 29.