Suppression of Higgs flavor-changing neutral currents in a class of gauge theories

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It is shown that the masses of neutral Higgs particles in the minimal $SU(2)_L \times SU(2)_R \times U(1)$ left-right-symmetric gauge theory which mediate flavor-changing interactions can be as large as necessary without running into conflict with experiment or with the validity of perturbation theory.

The accumulated neutral-current data strongly support the "standard" Weinberg-Salam[1] gauge theory of weak and electromagnetic interactions with the hadrons treated through the Glashow-Iliopoulos-Maiani[2] mechanism. However, left-right-symmetric gauge theories[3] suggested a few years ago with the minimal Higgs sector agree with the predictions of the standard model if $m_{W_R} \gtrsim 3m_{W_L}$, where W_L^+ and W_R^+ are left- and right-handed charged gauge mesons. Since they provide an explanation for the observed parity violation in nature and also predict an interesting theory of milliweak CP violation,[4] where CP and P are linked, they are appealing candidates for the theory of weak interactions. Additional interesting features such as Cabbibo-angle[5] and CP-phase[6] determinations, and suppression of strong CP violation[7] have been known for a while already. However, one less appealing feature of this theory is that although gauge-meson-mediated neutral currents naturally conserve flavor, Yukawa-type interactions do violate strangeness and charm. Of course, these effects can always be made small by assuming the relevant Higgs mesons to be much heavier than W_L. But since it is known[8] that the validity of perturbation theory in the ϕ^4 coupling constant in the standard model restricts the physical Higgs particle to be lighter than 1 TeV, the question can and should be raised whether similar considerations in left-right-symmetric models may dangerously reduce the masses of Higgs scalars, as to lead to experimentally forbidden large $\Delta S = 2$ effects. Also, in any theory with rich Higgs structure the relation $M_W^2 - M_Z^2\cos^2\theta$ gets possibly large contributions of order $g^2 m_H^2$,[9] which again limit the mass m_H of relevant Higgs particles.

In this note we analyze these questions in detail and show that the relevant Higgs-particle masses can be as large as necessary without any conflict with experiment and without invalidating perturbation theory.

We begin by reviewing some of the basic properties of the minimal left-right-symmetric $SU(2)_L \times SU(2)_R \times U(1)$ gauge theory. The quarks (and similarly leptons) are symmetrically placed in left and right doublets

$$Q_{iL}^0 = \begin{pmatrix} \mathcal{P}_i^0 \\ \mathcal{N}_i^0 \end{pmatrix}_L, \quad Q_{iR}^0 = \begin{pmatrix} \mathcal{P}_i^0 \\ \mathcal{N}_i^0 \end{pmatrix}_R, \tag{1}$$

with $\mathcal{P}_i^0$ and $\mathcal{N}_i^0$ counting up and down quarks, respectively (the superscript 0 denotes that they are not physical states, that is, not eigenstates of mass matrices). The minimal Higgs sector which provides quark masses and breaks the symmetry is

$$\begin{aligned} &\phi(\tfrac{1}{2}, \tfrac{1}{2}, 0) = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \\ &\chi_L(\tfrac{1}{2}, 0, 1) = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R(0, \tfrac{1}{2}, 1) = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}, \end{aligned} \tag{2}$$

where the quantum numbers in the brackets correspond to the representation content of $SU(2)_L$, $SU(2)_R$, and $U(1)$ respectively. The symmetry-breaking pattern which breaks parity spontaneously is

$$\langle\phi\rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix}, \quad \langle\chi_L\rangle = 0, \quad \langle\chi_R\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}. \tag{3}$$

We choose all the parameters real, since for simplicity we will ignore CP violation.

In order to discuss Higgs neutral currents we display the Yukawa couplings

$$\mathcal{L}_Y = \overline{Q}_{iL}^0 (a_{ij}\phi + b_{ij}\tilde{\phi}) Q_{jR}^0 + \text{H.c.}, \tag{4}$$

where $\tilde{\phi} \equiv \tau_2 \phi^* \tau_2$. From (3) and (4) one obtains the following quark mass matrices:

$$\begin{aligned} M_{ij}^P &= a_{ij}k + b_{ij}k', \\ M_{ij}^N &= b_{ij}k + a_{ij}k'. \end{aligned} \tag{5}$$

Since left-right symmetry leads to the condition

$a_{ij}=a_{ji}$, $b_{ij}=b_{ji}$, the quark mass matrices are real and symmetric. They can be diagonalized by orthogonal transformations and quark fields—we introduce the notation

$$P=\begin{pmatrix}\mathcal{P}_1\\ \mathcal{P}_2\\ \cdot\\ \cdot\\ \cdot\end{pmatrix},\quad N=\begin{pmatrix}\mathcal{N}_1\\ \mathcal{N}_2\\ \cdot\\ \cdot\\ \cdot\end{pmatrix}:$$

$$P^0_{L,R}=O_P P_{L,R}\,,\qquad N^0_{L,R}=O_N N_{L,R}\,, \tag{6}$$

so that

$$O_P^T M_P O_P=D_P\,,\qquad O_N^T M_N O_N=D_N\,, \tag{7}$$

where D_P and D_N are diagonal up- and down-quark mass matrices. Their physical meaning is clear, if we remember that the Cabibbo rotation is given by $O_C=O_P^T O_N$.

We can rewrite the Yukawa couplings in terms of physical quark states. We will work in the approximation $k'\ll k$, which is necessary in order to suppress W_L^+-W_R^+ mixing, as dictated by experiment. The choice $k'\ll k$ is not a natural one in the technical sense of the word, but since we have given up naturalness in the Higgs sector and since it is perfectly consistent, we will use it without further apology. We concentrate on the down quarks, since the strangeness violation in neutral currents is known to be tremendously suppressed (we will discuss the charm-changing phenomena later). We have for the piece that violates strangeness (we work for simplicity with 4 quarks, the generalization to a higher number of quarks being trivial)

$$\mathcal{L}_Y=\frac{1}{k}[\bar N_L O_C^T D_P O_C N_R \phi_2^0]+\text{H.c.} + (\text{terms of order } k'/k)\,. \tag{8}$$

We rewrite it in the form [we define $\phi_2^0\equiv(H_1+iH_2)/\sqrt{2}$]

$$\mathcal{L}_Y^{\Delta S=1}=-g\,\frac{m_c}{m_{W_L}}\,\frac{\cos\theta_c\sin\theta_c}{2}\,(\bar d s H_1+i\bar d\gamma_5 s H_2)\,, \tag{9}$$

where we keep the piece proportional to the charmed-quark mass, since $m_u\ll m_c$.

The diagonalization[10] of the Higgs sector shows that in the limit $k'\ll k$, H_1, and H_2 are physical states (eigenstates of the mass matrix) with masses

$$m_{H_1}{}^2\simeq m_{H_2}{}^2\simeq \alpha v^2\,, \tag{10}$$

where α is a particular combination of ϕ^4 coupling constants (notice that their masses are proportional to the heavy scale of the theory—that will be crucial for our future arguments). Now, from the well known suppression of $\Delta S=2$ processes, one can easily conclude that both H_1 and H_2 masses should be of order TeV or larger.

We present first a simple argument which illustrates why H_1 and H_2 can be desirably heavy. Namely, in the standard model $m_H{}^2=(\lambda/g^2)m_W{}^2$, where H is a physical Higgs scalar and λ is the ϕ^4 coupling constant, which restricts m_H to be *less* than 1 TeV, for the validity of perturbation theory in λ. By the similar argument, since $m_{H_i}{}^2 \simeq(\alpha/g^2)m_{W_R}{}^2$, we can expect $m_{H_i}<(1\text{ TeV})\; m_{W_R}/m_{W_L}$ which can be as large as necessary, and will be determined once the mass of W_R^+ is known (experimentally, we know only the lower bound on that ratio: $m_{W_R}/m_{W_L}\gtrsim 3$). As noted before, it is essential that $m_{H_i}\propto m_{W_R}$.

We now elaborate in detail on the possible processes which provide bounds on Higgs-scalar masses and whose precise results improve the above simple argument.

First, we calculate the one-loop corrections to the quantity $\Delta=(M_{W_L}{}^2-M_Z{}^2\cos^2\theta)/M_{W_L}{}^2$, which come from H_1 and H_2, to see if the experimentally known result $\Delta<5$–10% implies upper bounds on m_{H_i}. At the tree level, $\Delta_0=O(m_{W_L}{}^2/m_{W_R}{}^2)$ and is therefore negligible in the limit of heavy W_R^+. The graphs which involve H_1 and H_2 are shown in Fig. 1. We isolate only the leading terms of order $g^2 m_{H_i}{}^2/m_{W_L}{}^2$. A simple calculation gives for the H_i contribution to Δ

$$(\Delta)_{H_i}=\frac{1}{16\pi^2}\frac{g^2}{4m_{W_L}{}^2}[I(\phi_1^+,H_1)+I(\phi_1^+,H_2)-I(H_1,H_2)]\,, \tag{11}$$

where

$$I(1,2)=\frac{m_1{}^2m_2{}^2}{m_1{}^2-m_2{}^2}\ln\frac{m_1{}^2}{m_2{}^2}-\tfrac{1}{2}(m_1{}^2+m_2{}^2)\,. \tag{12}$$

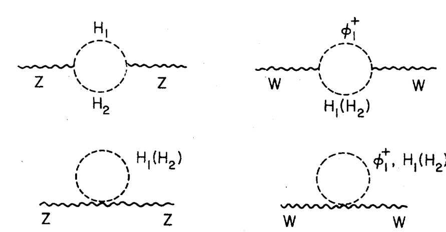

FIG. 1. The Higgs-particles H_1 and H_2 contribution to the quantity $\Delta=(M_{W_L}{}^2-M_Z{}^2\cos^2\theta)/M_{W_L}{}^2$.

We omit the details of the calculation, since these types of graphs have been treated before.[9] Now, the interesting result is obtained when $m_1^2 - m_2^2 \ll m_1^2$.

Namely, then

$$I(1,2) \underset{m_1^2 \to m_2^2}{\simeq} -\frac{1}{6}\frac{(m_1^2 - m_2^2)^2}{m_1^2}. \quad (13)$$

Obviously, when $m_1 = m_2$, $I(1,1) = 0$. Since in the limit $k' = 0$ one gets $m_{H_1} = m_{H_2}$, then $I(H_1, H_2) = O((k'^2/k^2) m_{W_L}^2)$. Also, one can show[10] that

$$m_{\phi_1^+}^2 = \alpha v^2 + \beta k^2 = m_{H_i}^2 + O(k^2), \quad (14)$$

where β is some ϕ^4 coupling. Since $v^2 \gg k^2$, obviously then $m_{\phi_1^+}^2 - m_{H_i}^2 \ll m_{H_i}^2$. We can then write

$$(\Delta)_{H_i} = -\frac{1}{16\pi^2}\frac{g^2}{12}\frac{(m_{H_i}^2 - m_{\phi_1^+}^2)^2}{m_{H_i}^2 m_{W_L}^2} \ll g^2, \quad (15)$$

which obviously provides no bound on the masses of H_i—they could be arbitrarily large. The key point is that the leading (order v) contribution to $m_{\phi_1^+}$ is the same as for m_{H_i}.

Actually, one could expect the above result. Since in the limit $k \to 0$, $m_{W_0} = m_{Z_0} = 0$ at the tree level and the $SU(2)_L \times U(1)$ subgroup is still unbroken, one does not expect W and Z to pick masses in higher orders proportional to v, since that would violate gauge invariance. That explains why Δ becomes proportional to $m_{\phi_1^+}^2 - m_{H_i}^2$ which is of order k^2, and is small compared to individual masses. One can easily be convinced that no effect of order v should correct Δ, since the heavy particles decouple.[11,12]

However, that is not the whole story. A few years ago Lee, Quigg, and Thacker[8] noticed within the context of the standard model that if the Higgs particle is too heavy, certain unitarity bounds would be violated at high energies in the lowest order and perturbation theory could not be trusted (weak interactions would become strong). From our naive argument given before, we expect such limits on Higgs masses to be pushed above by M_{W_R}/M_{W_L} or k/k' and therefore made as large as necessary. We now show that explicitly. We will discuss, at the lowest order, the high-energy scattering of longitudinally polarized gauge mesons. We need concentrate only on Higgs scalars H_1 and H_2 in order to show that their masses will not be severely limited (see Fig. 2). From Fig. 2 it is obvious that the relevant couplings are of the form gauge-meson–gauge-meson–Higgs-particle. We display them below:

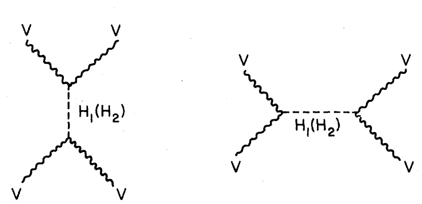

FIG. 2. Graphs involving H_1 and H_2 which contribute to the tree level scattering of gauge mesons. V denotes all possible gauge mesons, consistent with electric-charge conservation.

$$\Gamma_{vvH} = \frac{1}{2}\frac{g}{\cos\theta} m_Z \frac{k'}{k} H_1 Z_\mu Z^\mu + \frac{1}{\sqrt{2}} g m_{W_L} \frac{k'}{k} H_1 (W_{L\mu}^- W_L^{+\mu} + W_{R\mu}^- W_R^{+\mu}) - g m_{W_L} W_{L\mu}^+ W_R^{-\mu} (H_1 - iH_2) + \text{H.c.} \quad (16)$$

We now discuss the process $W_L^- W_L^+ \to W_L^- W_L^+$ in some detail. For this process Lee *et al.*[8] obtained in the standard model

$$M_H \le M_C = \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \simeq 1 \text{ TeV}. \quad (17)$$

Now, since $\Gamma_{W_L W_L H_1} = (\Gamma_{WWH})_{\text{WS}} k'/k$, it is obvious that the upper limit on m_{H_1}, which still guarantees the validity of perturbation theory, is

$$m_{H_1} \le \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \frac{k}{k'}, \quad (18)$$

which can be made as large as one wishes, by choosing k' sufficiently small. For example if $k/k' \sim 10$, then $m_{H_1} \le 10$ TeV, which is certainly large enough to suppress all strangeness-changing neutral-current phenomena. Obviously, the only exception to this is the process $W_L^- W_R^+ \to W_L^- W_R^+$, since then couplings of H_i are not suppressed by k'/k. However, in this case, the polarization effects are obviously of the form $q^4/m_{W_L}^2 m_{W_R}^2$, compared to the expression q^4/m_W^4 in the standard model. Therefore, again the bound on m_{H_i} is increased by m_{W_R}/m_{W_L} as compared to the standard model, that is,

$$(m_{H_i})_c = (m_H)_c^{\text{WS}} \frac{m_{W_R}}{m_{W_L}}, \quad (19)$$

where the subscript c denotes the critical values. Therefore, we are safe. Obviously, the exact nature of the bound (19) will be known only when the mass of the right-handed gauge meson is determined, that is, when (and if) the right-handed currents manifest themselves.

In conclusion, we have shown in the context of the minimal left-right-symmetric model that the masses of neutral Higgs scalars which mediate $\Delta S = 1$ and $\Delta S = 2$ processes can easily be of order TeV or larger and still to account for the validity of perturbation theory and the experimental success of the relation

$$\Delta = \frac{M_{W_L}{}^2 - M_Z{}^2 \cos^2\theta}{M_{W_L}{}^2} \simeq 0 .$$

What about charm-changing neutral-current phenomena? The reader can easily convince herself (himself) that ϕ_1^0 conserves flavor in the limit $k' \to 0$; therefore its contribution is suppressed by k'/k and so can be made small. Now, ϕ_2^0 leads to charm-changing effects but obviously negligibly compared to the known suppression[13] of such processes. In conclusion, in the limit $k' \to 0$, ϕ_1^0 conserves flavor, ϕ_2^0 does not, but then all such effects are controlled by $k'/k \ll 1$ or $m_{w_L}/m_{w_R} \ll 1$.

For the reader who prefers theories with natural flavor conservation, we wish to bring to her (his) attention the class of left-right-symmetric models which conserve light-quark flavors[14] (of course, not all quark flavors can be conserved, as the analysis of Glashow and Weinberg[15] tells us). These theories have an interesting b-quark physics[16] and have naturally massless neutrinos.[14]

We would like to add that recently an interesting trick has been suggested by Georgi and Nanopoulos,[17] which would enable one to make the neutral Higgs bosons in the $SU(2)_L \times U(1)$ theory with two or more doublets heavy, as to suppress $\Delta S = 2$ processes. However, in left-right symmetric theories, as we have seen, these particles are necessarily heavy, since their masses originate from the heavy scale in the theory (the same that is responsible for the $V+A$ charged current).

It would be interesting to see whether the same kind of results discussed here would be true in a theory that also has calculable Cabibbo-type angles and (or) a CP-violating phase. It is our intention to address ourselves to this question in a separate note.

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