The heavy top quark and right-handed currents

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Abstract

We consider a modification of the standard electroweak model with the third quark generation and the τ-lepton in vector representations of $SU(2) \otimes U(1)_Y$ electroweak symmetry. This is a new way to implement right-handed currents which are controlled by the usual Fermi constant, $G_F$, the weak mixing angle, $\sin \theta_W$, and also by the right-handed mixing matrices which survive when the Lagrangian density is written in terms of the mass eigenstates. In this case there are also new CP violation phases.

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I. INTRODUCTION

The standard model of the elementary particles based on the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ is in agreement with almost all experimental data. Data which are not easily accommodated in this model are not definitive yet. The electroweak part of this model is built in such a way that all charged currents are purely left-handed and parity is maximally violated in weak processes. Thus, the electroweak standard model (ESM) is a complete chiral model, i.e., the left-handed fermions transform in a different way than the right-handed ones do. Moreover, all generations transform in the same way and this is the reason why parity is maximally violated in all of them.

Since the left-handedness of the bottom quark has not been experimentally tested yet with the same precision than that obtained in the measurements for the other fermions, it has been pointed out, recently, that in the context of $SU(2)_L \otimes SU(2)_R \otimes U(1)$ electroweak models, this quark may decay through, in the extreme case, purely right-handed. A more realistic situation is to assume that the third generation has right-handed currents which are not dominant in the weak decay of the $b$-quark. This issue will be set by studying the decay of polarized $\Lambda_b$, in the $b \to s\gamma$ decay or, as it will be argued below, in some processes at the $Z^0$-peak energy.

In fact, in literature when right-handed currents among the known generations are considered it is mainly done in the context of models involving right-handed gauge bosons, like in the left-right symmetric models mentioned above. In this case the effect of right-handed currents (and any correction to the results obtained with the ESM) are controlled chiefly by the two parameters: the mass of the new gauge bosons in the form of the parameter $\delta = (M_L/M_R)^2$, with $M_L \approx M_W$ and the mixing angle $\zeta$ among left- and right-handed vector bosons.

Here we will show that it is possible to have right-handed currents controlled by the usual parameters $G_F$, $\sin \theta_W$, and also by the right-handed mixing matrices which survive in the Lagrangian density. These right-handed mixing angles and phases may be important only for the third generation, keeping consistency with the phenomenology of the first two generations. We recall that, although parity violation has been tested mainly with the first and second generations it may not necessarily happen with the third generation. Hence, even in the context of a $SU(2) \otimes U(1)$ model we can have right-handed currents because new parameters, that are not constrained in the context of the ESM, survive in the Lagrangian density when one of the generations transforms in a vector way under the electroweak symmetry. We call this type of models quasi-chiral models.

Before going on this new way to implement right-handed currents, we first emphasize some features of the mass matrices for quarks in the context of the ESM. In this model, in order to diagonalize the quark mass matrices it is necessary to introduce unitary matrices $V^{U}_{L,R}$ and $V^{D}_{L,R}$ in both chiral (left- and right fields) and charge ($u$- and $d$-like) sectors. There is also automatic flavor conservation in both, neutral Higgs-fermion and neutral vector-fermion interactions. This implies that the right-handed mixing matrices $V^{U}_{R}$, $V^{D}_{R}$ disappear when the Lagrangian density is written in terms of the quark mass eigenstates $U = (u, c, t, \ldots)^T$ and $D = (d, s, b, \ldots)^T$. Only the left-handed mixing matrices $V^{U}_{L}$ and $V^{D}_{L}$ remain in the charged current coupled to the $W^\pm$: $\bar{U}_L V_{CKM} \gamma^\mu D_L W^- \mu$ where $V_{CKM} = V^{Ud}_{L} V^{Uu}_{L}$ denotes the Cabibbo-Kobayashi-Maskawa mixing matrix. Thus, no trace of the matrices $V^{U,D}_{L,R}$ separately is left...
in the Lagrangian density of the ESM. However, as we will show below, this argument is not valid when at least one generation is assigned to a vector representation of $SU(2) \otimes U(1)_Y$.

Summarizing, the main goal of this work is to show that: if we consider the electroweak interactions in a quasi-chiral model, with the left- and right-handed components of the third generation transforming as doublets under $SU(2)$, the right-handed mixing matrices survive after the diagonalization of the mass matrices. Another interesting consequence is that the physical phases in the Lagrangian density are more than one, that is, new sources of CP violation arise too in this context (see Sec. V).

This work is organized as follows. In Sec. II we present the modification of the standard electroweak model in which the third generation belongs to a vector representation of $SU(2) \otimes U(1)_Y$. The Yukawa interactions are given in Sec. III while gauge interactions are considered in Sec. IV. Our conclusions and some phenomenological considerations appear in the last section.

II. A MODIFIED $SU(2) \otimes U(1)_Y$ MODEL

As we said before, in this work we consider a version of the ESM in which the third family is in a vector representation of $SU(2) \otimes U(1)_Y$. We define the electric charge operator as usual, $Q/e = I_3 + Y/2$, so that the quark sector in this model is

$$Q^i_L = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L \sim \left( \begin{array}{c} 2 \\ \frac{1}{3} \end{array} \right); \quad u^i_R \sim \left( \begin{array}{c} 1 \\ \frac{4}{3} \end{array} \right), \quad d^i_R \sim \left( \begin{array}{c} 1 \\ \frac{-2}{3} \end{array} \right), \quad i = 1, 2; \quad (1)$$

as in the ESM, but with the third quark generation transforming as

$$Q^3_L = \begin{pmatrix} u^3 \\ d^3 \end{pmatrix}_L, \quad Q^3_R = \begin{pmatrix} u^3 \\ d^3 \end{pmatrix}_R \sim \left( \begin{array}{c} 2 \\ \frac{1}{3} \end{array} \right). \quad (2)$$

The Higgs boson sector consists of the usual doublet $\varphi = (\varphi^+, \varphi^0)^T$, a singlet $\phi \sim (1, 0)$ and a triplet: $H \sim (3, 0)$

$$\vec{H} \cdot \vec{\tau} = \begin{pmatrix} H_T^0 \\ \sqrt{2}H^+ \\ -H_T^- \end{pmatrix}, \quad (3)$$

with $\vec{\tau}$ being the Pauli matrices. The shifted neutral fields are defined as $\varphi^0 = (1/\sqrt{2})(v_D + H_T^0)$, $\phi = (1/\sqrt{2})(v_S + H_T^0)$ and $H_T^0 = (1/\sqrt{2})(v_T + H_T^0)$, and we will assume $v_S > v_D \gg v_T$. We can always choose $v_D$ real by an appropriate $SU(2)$ transformation. The triplet does not contribute to the mass of the $Z$ but it does to the $W$ mass. Hence we have new contributions to the $\rho$ parameter which measures the strength of the neutral current interaction relative to the charged current interaction and that at tree level in this model is defined as $\rho = M_W/M_Z \cos \theta_W = 1 + 4(v_T/v_D)^2$. The global fit for this ratio is $1.0012 \pm 0.0015 \pm 0.0013$ [2]. It means that $v_T \approx 9.7$ GeV in order to be consistent with data, say at 2 standard deviations. At higher order there will be other contributions to $\Delta \rho$ as in the ESM but these have to be computed in the context of the present model. The value of $v_S$, of course, is not constrained by present experimental data.
Next, let us consider leptons. To put the tau lepton and its neutrino in a vector representation of $SU(2)$ might be inconsistent with phenomenology. However, we can introduce a fourth lepton family and neutral singlets in order to have more room for experimental data, especially the $Z$-invisible width and also for maintaining the model anomaly free. Then we have the left-handed fields transforming as $(2, -1)$

$$\Psi_{eL} = \left( \nu_e, e^{-} \right)_L, \quad \Psi_{\mu L} = \left( \nu_{\mu}, \mu^{-} \right)_L, \quad \Psi_{\tau L} = \left( \nu_{\tau}, \tau^{-} \right)_L, \quad \Psi_{TL} = \left( \nu_t, T^{-} \right)_L;$$

right-handed components transforming also as $(2, -1)$

$$\Psi_{eR} = \left( N_1, \tau^{-} \right)_R, \quad \Psi_{TR} = \left( N_2, T^{-} \right)_R.$$

Finally, the singlets $N_{1L}, N_{2L} \sim (1, 0)$ and $e_R, \mu_R \sim (1, -2)$.

It is interesting to notice that it is possible to embed this model in a gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ as in the model proposed some years ago by Georgi and Pais \[9,10\]. In order to do this we must introduce extra quarks with left- and right-handed components transforming as singlets under $SU(2)$: two with charge $-1/3$, say $s'$ and $b'$, and one with charge $2/3$, say $t'$. This isosinglets have effects on $Z \rightarrow b\bar{b}, c\bar{c}$ \[11\] that eventually must be considered in the phenomenology of the model. Here we will not consider this possibility.

## III. Yukawa Interactions

Let us now consider the generation of the fermion masses. In the quark sector, the Yukawa interactions are

$$-\mathcal{L}_Y = \sum_{i,j} Q_{iL} [A_{ij} u_{jR} \tilde{\varphi} + B_{ij} d_{jR} \varphi] + \sum_i Q_{3L} [a_i u_{iR} \tilde{\varphi} + b_i d_{iR} \varphi]$$

$$+ \sum_\alpha h_\alpha \bar{Q}_{\alpha L} Q_{3R} \varphi + \sum_{\alpha,i,j} h'_\alpha \bar{Q}_{\alpha iL} Q_{3jR} (\bar{H} \cdot \tilde{\tau})_{ij} + H.c.,$$

where $i, j = 1, 2$ and $\alpha = 1, 2, 3$. All coupling constants $A$'s, $B$'s, $a$'s, $b$'s $h$'s and $h'$'s are, in principle, complex numbers.

In the quark sector we have from Eq. (5) the mass matrices

$$M^U = \frac{v_S}{\sqrt{2}} \begin{pmatrix} A_{11r} & A_{12r} & h_1 \\ A_{21r} & A_{22r} & h_2 \\ a_{1r} & a_{2r} & h_3 + h'_3 r' \end{pmatrix}, \quad M^D = \frac{v_S}{\sqrt{2}} \begin{pmatrix} B_{11r} & B_{12r} & h_1 \\ B_{21r} & B_{22r} & h_2 \\ b_{1r} & b_{2r} & h_3 - h'_3 r' \end{pmatrix},$$

with the notation $r = v_D/v_S$, $r' = v_T/v_S$. We have assumed, for the sake of simplicity, a discrete symmetry allowing only the third generation to couple with the triplet. Notice that, since there are three scalars contributing to the mass matrices, there are flavor changing neutral currents (FCNC).

The scalar triplet breaks strongly the isospin symmetry. For simplicity we will assume that $h_3, h'_3 > 0$. We see from Eq. (3) that $m_t \approx (v_s/\sqrt{2})(h_3 + h'_3 r')$ and $m_b \approx (v_s/\sqrt{2})(h_3 - h'_3 r')$, so that $m_t - m_b = \sqrt{2}v_T h'_3$ and $m_t + m_b = \sqrt{2}v_S h_3$. Thus, we have that if $v_T = 9.7$ GeV,
\[ m_t = 179 \text{ GeV} \text{ and } m_b = 4.5 \text{ GeV}, \ h_3 \approx 0.32 \ (h_3^2/4\pi \approx 0.008) \text{ and } h'_3 \approx 13 \ (h'_3^2/4\pi \approx 13) \]

and it appears that at least the third generation interacts strongly with the Higgs triplet. This sort of scalar could be implemented by a dynamical symmetry breaking where the Higgs bosons appear as condensates of the fermions present in the model, but we will not speculate about this issue here.

In general, these mass matrices can be diagonalized using unitary matrices \( V^U_{L,R} \) and \( V^D_{L,R} \) defined as follows:

\[
U'_L = V^U_L U_L, \quad U'_R = V^U_R U_R; \quad D'_L = V^D_L D_L, \quad D'_R = V^D_R D_R, \quad (7)
\]

where \( U' = u_1, u_2, u_3 \) and \( D' = d_1, d_2, d_3 \) are symmetry eigenstates, while \( U = u, c, t \) and \( D = d, s, b \) are mass eigenstates. Mass matrices in Eq. (7) are general enough to generate the mass spectra \( m_t \gg m_c > m_u; \ m_b > m_s > m_d \).

From Eq. (7) we have the quark-scalar interactions

\[
-\mathcal{L}_Y = \bar{U}_L \left[ \frac{\hat{M}^U}{v_D} - \frac{1}{r} V^U_L \Omega V^U_R \right] U_R H'^0_1 + \bar{D}_L \left[ \frac{\hat{M}^D}{v_D} - \frac{1}{r} V^D_L \Omega V^D_R \right] D_R H'^0_1 \\
+ \left[ \bar{U}_L V^{U*}_L \Omega V^U_R U_R + \bar{D}_L V^{D*}_L \Omega V^D_R D_R \right] H'^0_2 \\
+ \left[ \bar{U}_L V^{U*}_L \Omega V^U_R U_R + \bar{D}_L V^{D*}_L \Omega V^D_R D_R \right] H'^0_3 \\
+ \sqrt{2} h'' \left( \bar{D}_L V^D_L \Delta V^U_R U_R H^- + \bar{U}_L V^U_L \Delta V^D_R D_R H^+ \right) + H.c. \quad (8)
\]

where \( \hat{M}^U, \hat{M}^D \) are the diagonal mass matrices for the \( u \)-like and \( d \)-like quarks, respectively, \( \Delta = \text{diag}(0, 0, 1) \) and

\[
\Omega = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & h_1 \\ 0 & 0 & h_2 \\ 0 & 0 & h_3 \end{pmatrix}, \quad \Omega^\pm = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \pm h'_3 r' \end{pmatrix}. \quad (9)
\]

We see that in the interactions of quarks with the scalar \( H'^0_1 \) the factor \( 1/r > 1 \) appears. However, since the mixing matrices \( V^{U*}_L \Omega V^U_R \) and \( V^{D*}_L \Omega V^D_R \) also appear, these interactions are not necessarily strong. The interactions with the scalar \( H'^0_3 \) are proportional to \( h'' \), so, they also are not strong. On the other hand, the interactions with the charged scalars \( H^{\pm} \) are proportional to \( h'_3 \), hence, these are in principle, strong interactions depending on the values of the parameters in \( V^{U*}_L \Delta V^U_R \) and \( V^{D*}_L \Delta V^D_R \). The matrices \( V^{L,D}_{L,R} \) also control the flavor changing neutral currents in the scalar sector. Recall too that the fields \( H'^0_{1,2,3} \) in Eq. (8) are not the mass eigenstates yet.

The Yukawa interactions in the lepton sector are

\[
-\mathcal{L}_l = \sum_{a,b} \bar{\psi}_{aL} G_{ab} l_{bR} \phi + \sum_{a,\alpha} \bar{\psi}_{aL} h_{aa} N_{\alpha R} \tilde{\phi} + \sum_{m,\alpha} \bar{\psi}_{mR} F_{ma} N_{\alpha L} \tilde{\phi} \\
+ \sum_{a,m} \bar{\psi}_{aL} H_{am} \psi_{mR} \phi + \frac{1}{2} \sum_{a,\alpha} \tilde{N}_{aL} h'_{a\alpha} N_{\alpha R} \phi + \sum_{m,n,i,j} \bar{\psi}_{niL} H'_{mn} \psi_{njR} (\tilde{H} \cdot \tilde{\tau})_{ij} + H.c. \quad (10)
\]

where \( l_{bR} = e_R, \mu_R \); \( G_{ab}, h_{aa}, H_{am}, F_{ma} \) and \( h'_{a\alpha} \) denote arbitrary complex dimensionless constants, \( a = e, \mu, \tau, T \); \( m, n = \mu, T \) and \( \alpha, \beta = 1, 2 \). From Eq. (10) we obtain an arbitrary \( 4 \times 4 \) mass matrix for charged leptons. On the other hand, assuming \( G_{ab} v_D, H'_{mn} v_T <
$H_{am}v_S \ll F_{ma}v_D$, the neutral leptons $N_\alpha$ are heavier than the charged leptons. In fact, if we also assume $h_{aa}v_D < h'_{\alpha\beta}v_S \ll F_{ma}v_D$, then the $N_\alpha$’s have its mass matrix dominated at tree level by the term $v_D\tilde{N}_\alpha R F_{\alpha\beta} N_{\beta L}$. We have too the mass term $\frac{1}{2}\bar{\psi}_\nu L M_{\psi_R}^c$, where $\psi_{\nu L} = (\nu_e L, \nu_\mu L, \nu_\tau L, \nu_T L, N_{c1L}, N_{c2L})^T$ and

$$M \approx v_S \begin{pmatrix}
0 & 0 & 0 & 0 & h_{e1r} & h_{e2r} \\
0 & 0 & 0 & 0 & h_{\mu1r} & h_{\mu2r} \\
0 & 0 & 0 & 0 & h_{T1r} & h_{T2r} \\
0 & 0 & 0 & 0 & h_{e1r} & h_{T1r} \\
0 & 0 & 0 & 0 & h_{e2r} & h_{T2r} \\
\end{pmatrix}.$$  (11)

This matrix has two eigenvalues equal to zero and four others different from zero. It is possible, as in the case of three lepton doublets and one neutral singlet [12], to fit the $Z^0$ invisible width without assuming a see-saw hierarchy in Eq. (11).

**IV. GAUGE INTERACTIONS**

The neutral current interactions of fermions $\psi_i$ can be written as usual

$$\mathcal{L}^{NC} = -\frac{g}{2c_W} \left[ \sum_i L_i \bar{\psi}_i L \gamma^\mu \psi_i + R_i \bar{\psi}_i R \gamma^\mu \psi_i \right] Z_\mu,$$

$$= -\frac{g}{2c_W} \sum_i \bar{\psi}_i \gamma^\mu (g_{V_i} - \gamma^5 g_{A_i}) \psi_i Z_\mu,$$  (12)

where $g_{V_i} \equiv \frac{1}{2}(L_i + R_i)$, $g_{A_i} \equiv \frac{1}{2}(L_i - R_i)$ and $c_W \equiv \cos \theta_W$. Thus, we have (using also $s_W^2 \equiv \sin^2 \theta_W$)

$$L_{d1} = L_{d2} = L_{d3} = -1 + \frac{2}{3}s_W^2 \equiv L_D;$$

$$R_{d1} = R_{d2} = \frac{2}{3}s_W^2 \equiv R_D, \quad R_{d3} = -1 + \frac{2}{3}s_W^2 \equiv R_D';$$

for the charge $-1/3$ sector, and

$$L_{u1} = L_{u2} = L_{u3} = 1 - \frac{4}{3}s_W^2 \equiv L_U;$$

$$R_{u1} = R_{u2} = -\frac{4}{3}s_W^2 \equiv R_U, \quad R_{u3} = 1 - \frac{4}{3}s_W^2 \equiv R_U';$$

for the charge 2/3 sector. Here $L_D, R_D$ and $L_U, R_U$ denote the ESM couplings for the respective charge sector.

For the leptons we have

$$L_{\nu_a} = 1, \quad L_{\alpha} = -1 + 2s_W^2, \quad a = e, \mu, \tau, T; \quad L_{N_\alpha} = 0, \quad \alpha = 1, 2;$$  (15a)
\[ R_{\nu_a} = 0, \quad R_e = R_\mu = 2s_W^2, \quad R_\tau = R_T = -1 + 2s_W^2, \quad R_{N_a} = 1. \]  

(15b)

Notice that the singlets \( N_a \) have only right-handed neutral currents.

The left-handed neutral currents in Eq. (12) can be rewritten, in the \( d \)-like sector, as

\[
\mathcal{L}_{dL}^{NC} = -\frac{g}{2c_W} L_D (\bar{d}_1 \, \bar{d}_2 \, \bar{d}_3) L \gamma^\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}_L Z_\mu, \tag{16}
\]

and we see that this interaction is diagonal in terms of the symmetry eigenstates. On the other hand, the respective right-handed neutral currents are

\[
\mathcal{L}_{dR}^{NC} = -\frac{g}{2c_W} (\bar{d}_1 \, \bar{d}_2 \, \bar{d}_3) R \gamma^\mu \begin{pmatrix} \frac{2}{3}s_W^2 & 0 & 0 \\ 0 & \frac{2}{3}s_W^2 & 0 \\ 0 & 0 & -1 + \frac{2}{3}s_W^2 \end{pmatrix} \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}_R Z_\mu. \tag{17}
\]

Both Eqs. (16) and (17), are given in terms of the symmetry eigenstates. When the transformations in Eq. (7) are done, the left-handed currents in Eq. (16) are still diagonal, thus the Glashow-Iliopoulos-Maiani (GIM) mechanism \[13\] is implemented at tree level in the left-handed currents for the charge \(-1/3\) sector. The same occurs in the left-handed charge \(2/3\) sector. Notwithstanding, this does not happen in the right-handed currents. Hence, there are flavor changing right-handed neutral currents (FCRN C) at tree level. When we turn to the mass eigenstates, Eq. (17) becomes, using the transformation given in Eq. (7),

\[
\mathcal{L}_{dR}^{NC} = -\frac{g}{2c_W} \bar{D}_R \gamma^\mu \left[ R_D 1 - V_{D}^{\dagger} \Delta V_{D}^{\dagger} \right] D_R Z_\mu, \tag{18}
\]

where \( D = (d, s, b) \) denotes the mass eigenstates, \( \Delta = \text{diag}(0, 0, 1) \) as in Sec. 11 and \( R_D = (2/3)s_W^2 \). We see that the FCRNC involves some elements of the matrix \( V_{D}^{\dagger} \) which do not survive in the standard model after the diagonalization of the mass matrix.

Similarly for the \( u \)-type quarks we have

\[
\mathcal{L}_{uR}^{NC} = -\frac{g}{2c_W} \bar{U}_R \gamma^\mu \left[ R_U 1 - V_{U}^{\dagger} \Delta V_{U}^{\dagger} \right] U_R Z_\mu, \tag{19}
\]

where \( U = (u, c, t) \) and \( R_U = -(4/3)s_W^2 \).

Concerning the charged currents of the model, besides the usual left-handed ones which coincide with the currents of the standard model, we have the contribution \( \bar{u}_3 \gamma^\mu d_3 \) that, in terms of the mass eigenstates is written as

\[
\mathcal{L}_{CC}^{R} = -\frac{g}{\sqrt{2}} (\bar{u} \, \bar{c} \, \bar{t})_R \gamma^\mu V_{R}^{U \dagger} \Delta V_{R}^{D} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R W^+ + H.c., \tag{20}
\]

and the only relevant parameters could be \( (V_{R}^{U \dagger} \Delta V_{R}^{D})_{wb} \) and \( (V_{R}^{U \dagger} \Delta V_{R}^{D})_{cb} \) (other matrix elements can be \( \approx 0 \)). Hence, the weak charged currents can still be predominantly left-handed as in the standard model \[14\]. Notice that in Eq. (20) both \( V_{R}^{U} \) and \( V_{R}^{D} \) do appear.
These new currents are controlled by the matrix elements of $V_R^{U\dagger}$ and $V_R^{D}$, besides $G_F$ and $\sin^2 \theta_W$ which also appear in the other standard currents. Neither the parameters in Eqs. (18) and (19) nor those in Eq. (20) appear explicitly in the standard model. As we said before, in the last case, only the combination $V_{\text{CKM}} = V_R^{U\dagger} V_R^{L}$ is left when the Lagrangian density is written in terms of the mass eigenstates. Hence, in this model it is possible that both, charged and neutral right-handed currents, couple mainly to the third family. (See also Sec. V).

In the leptonic sector we do not have the GIM mechanism at tree level in the right-handed neutral currents coupled to the $Z^0$ because the mass matrix mixes the $\tau$ lepton with the other charged leptons. So, there are also FCRNC effects. In terms of the mass eigenstates $e, \mu, \tau$ and $T$ we have the following interactions (in Eq. (4) the same notation denotes symmetry eigenstates)

$$L_{\text{NC}}^{lR} = \frac{g}{2c_W} \bar{e} \gamma^\mu \left( \begin{array}{ccc} \bar{\mu} & \bar{\tau} & \bar{T} \end{array} \right)_R \gamma^\mu V_R^{U\dagger} Y_l R \left( \begin{array}{c} e \\ \mu \\ \tau \\ T \end{array} \right)_R Z_\mu, \quad (21)$$

where $V_R^{l}$ is the $4 \times 4$ right-handed mixing matrix in the charged lepton sector and we have introduced $Y_l = \text{diag}(2s^2_W, 2s^2_W, -1 + 2s^2_W, -1 + 2s^2_W)$. We can write Eq. (21) as follows

$$L_{\text{NC}}^{lR} = \frac{g}{2c_W} l_R \gamma^\mu \left[ R_l - V_R^{U\dagger} \Delta_l V_R^{l} \right] l_R Z_\mu, \quad (22)$$

where $R_l = 2s^2_W$ and $\Delta_l = \text{diag}(0, 0, 1, 1)$. We see that after we have diagonalized the mass matrix of the charged leptons, the right-handed mixing matrix survives in Eq. (21).

The values of these new mixing parameters can be chosen in such a way that the model can be consistent with the measurements of $\tau$ asymmetries at LEP. In fact, it has been measured the ratio of vector to axial-vector neutral couplings and it has been found consistency with the hypothesis of $e - \tau$ universality [2]. There are measurements of the tau-neutrino helicity [14] and Michel parameters [15] which confirm a dominant left-handed $(V - A)$ structure in the charged current for the $\tau$ and its neutrino and by which pure vector $(V)$, axial-vector $(A)$ or right-handed $(V + A)$ interactions have been ruled out. However, in the present model we have $V + A$ interactions with almost arbitrary strength, so this experimental data will imply only constraints on some mixing angles in $V_R^{l}$. We recall that in this model there are also flavor changing neutral currents in the neutrino sector like in the model with a single neutral singlet [12]. Thus at tree level we can impose that in Eq. (22)

$$V_{R_{eaa}}^{l} V_{R_{ee}}^{l} \approx V_{R_{\mu a}}^{l} V_{R_{\mu e}}^{l} \approx V_{R_{\tau a}}^{l} V_{R_{\tau e}}^{l} \approx 0, \quad a = e, \mu, \tau; \quad (23)$$

with the other elements of the matrix with $a = T$ to be set up by other experimental data.

The charged currents of the phenomenological neutrinos $\nu_a$ ($a = e, \mu, \tau, T$) with all charged leptons are purely left-handed, as can be seen from Eq. (14a). However, when they are written in terms of the mass eigenstates, because $N_1$ and $N_2$ have purely right-handed couplings with $\tau^-$ and $T^-$ as can be seen from Eq. (14b), right-handed couplings among neutrino mass eigenstates and charged leptons will appear. So, we can write right-handed currents like in Eq. (20), in the leptonic sector. As there are six neutrinos but only four
charged leptons, it is possible to extend the column of the charged leptons with two zeros in such a way that the right-handed current is written in terms of $6 \times 6$ matrices involving both mixing matrices in charged and neutral sector. We will not write these interactions explicitly.

V. CONCLUSIONS AND PHENOMENOLOGICAL CONSEQUENCES

It is not our intention to make here a detailed study about the phenomenology of the model. We want only to point out some remarkable features. Up to present all experimental data have not been sufficiently to rule out deviation from the $V - A$ structure. In the context of the $L - R$ symmetric models they only put constrains on the parameters $\delta = (M_L/M_R)^2$ and the mixing angle $\zeta$. For instance, studying direct neutron beta decay as it is done in Ref. [6]. In the present model we have several parameters to be fitted with experimental data. Hence, we have more freedom than in $L - R$ models.

As we said before, almost all $Z^0$-pole observables are in agreement with the standard model predictions [3]. There are, however, some of them which are under special consideration at present because it seems that they do not agree completely with the model’s predictions. For example, the heavy quark production ratios

$$\frac{\Gamma(Z^0 \to q\bar{q})}{\Gamma(Z^0 \to \text{hadrons})} \equiv \frac{\Gamma_q}{\Gamma_h}, \quad \Gamma_h = \sum_q \Gamma_q,$$

(24)

that have been measured for $c$ and $b$ quarks. Until recently, $\Gamma_b/\Gamma_h$ and $\Gamma_c/\Gamma_h$ were in conflict with the ESM. Nowadays, although $Z \to c\bar{c}$ agrees with the theoretical predictions, $Z \to b\bar{b}$ lies some $1.8\sigma$ above the respective predictions of the ESM [3].

Another observable which is in disagreement with the standard model is the forward-backward asymmetry $A_{LR}^{(0,b)} \approx A_c A_b$, with $A_f$ defined as

$$A_f \equiv \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2} = \frac{(L_f)^2 - (R_f)^2}{(L_f)^2 + (R_f)^2}.$$  

(25)

The SLD data give

$$A_b = 0.882 \pm 0.068\,(\text{stat}) \pm 0.047\,(\text{sys}),$$

(26)

leading to a world average

$$A_b = 0.867 \pm 0.022,$$

(27)

about $3\sigma$ below the standard model prediction $A_b = 0.935$ [3].

These observables $\Gamma_b/\Gamma_h$ and $A_{LR}^{(0,b)}$ depend on the effective vector and axial-vector couplings $\bar{g}_V$ and $\bar{g}_A$, defined in Eq. (12), which in the ESM scenario include radiative corrections. In the context of our model $\bar{g}_V$ and $\bar{g}_A$ or $\bar{L}$’s and $\bar{R}$’s refer to the couplings defined in terms of the coefficients which incorporate the right-handed neutral currents in Eqs. (18), (19) and radiative corrections too. We will use the notation $\delta R_{ff'} \equiv \bar{R}_{ff'} - R_F = 2\delta_{RR}$ (or just $2\delta_{R}$, if $f = f'$) and we will write them only at tree level, $R_F$ denotes the ESM value.
without radiative corrections for all fermions of the same charge sector i.e., \( F = U, D \), while \( f, f' = d, s, b, u \) and \( c \). We write explicitly only the diagonal case \( f = f' \):

\[
\delta R_{dd} \equiv \bar{R}_d - R_D = (V_R^{\dagger} \Delta V_R^D)_{dd} = (V_R^{\dagger})_{bd} (V_R^D)_{bd} = 2\delta g_R^d; \quad (28a)
\]

\[
\delta R_{ss} \equiv \bar{R}_s - R_D = (V_R^{\dagger} \Delta V_R^D)_{ss} = (V_R^{\dagger})_{bs} (V_R^D)_{bs} = 2\delta g_R^s; \quad (28b)
\]

\[
\delta R_{bb} \equiv \bar{R}_b - R_D = (V_R^{\dagger} \Delta V_R^D)_{bb} = 2\delta g_R^b - 1 - 2\delta g_R^d - 2\delta g_R^s; \quad (28c)
\]

for the \( d \)-like sector, and

\[
\delta R_{uu} \equiv \bar{R}_u - R_U = (V_R^{\dagger} \Delta V_R^U)_{uu} = (V_R^{\dagger})_{tu} (V_R^U)_{tu} = 2\delta g_R^u; \quad (29a)
\]

\[
\delta R_{cc} \equiv \bar{R}_c - R_U = (V_R^{\dagger} \Delta V_R^U)_{cc} = (V_R^{\dagger})_{tc} (V_R^U)_{tc} = 2\delta g_R^c; \quad (29b)
\]

for the \( u \) and \( c \) quarks; the \( \delta \)'s on the right hand side denote the respective coefficients in the notation of Ref. [17]. The factor 2 arises because of the different parameterization between the neutral currents in our Eq. (12) and Eq. (2) in Ref. [17]. On the other hand, in the lepton sector we have from Eq. (21)

\[
\delta R_{ll} \equiv \bar{R}_l - R_L = - (V_R^{\dagger} \Delta V_R^l)_{ll} = 2\delta^l_R. \quad (30)
\]

where \( R_L \) denotes the ESM value for the charged leptons.

Using Eq. (28c), we can write Eq. (25) for \( f = b \) as

\[
A_b = \frac{L_D^2 - (R_D + \delta R_{bb})^2}{L_D^2 + (R_D + \delta R_{bb})^2}; \quad (31)
\]

and if \( \delta R_{bb} \approx 0.071 \) or \(-0.380 \) we obtain a value for \( A_b \) which is compatible with that in Eq. (27). Notice however that, from Eqs. (28), this implies that \( \delta R_{dd} = \delta R_{ss} \approx 0.35 \) or 0.23. Only a careful analysis looking for a correlation among all the parameters in the model may show if there is some range for these parameters fitting all these experimental data. It is possible to fit the \( Z \to b\bar{b} \) width (even if this width will coincide in the future with the numerical expectation of the standard model) and the \( A_{LR}^{(0,b)} \) asymmetry if at the same time the light quark and lepton contributions are appropriately modified. So, even assuming that all nondiagonal right-handed couplings are negligible, we have a possible correlation among the six parameters: \( \delta_R^b, \delta_R^c, \) and \( \delta_{UD} \) defined in our context as

\[
\delta g_{UD}^q = 4 \sum_{q=u,d,s} g_R^q \delta g_R^q; \quad (32)
\]

together with \( \delta_R^b, \delta_R^c \) and \( \delta_R^d \). We also stress that in the present model there are nonstandard \( W \) couplings, as in Eq. (20), and FCRNC effects parameterized by \( \delta R_{ab} \), etc. Independent of the anomaly in the \( A_b \) asymmetry to persist or not, it is necessary to look for direct evidence of the right-handed \( b \) couplings.
As we said before, it is well known that the leptonic charged currents are consistently left-handed [13,16] and also that the $c$ quark has a dominant left-handed structure [18]. However, these results put constrains only on the allowed values for some elements of the matrices $V_{L,R}^{U,D,I}$ entering in the first two generation processes. In fact, for the $c$ quark a small mixture of right-handed couplings can be accommodated by data. In $c$ meson decays, using the CDHS detector, the upper limit of 0.07 for the relative strength of the square of the $c \to s$ right-handed current has been obtained [18]. The measurement of the lepton decay forward-backward asymmetry in the reaction $\bar{B} \to D^* l^-\nu_l$ confirms that the chirality of the weak interactions in $b \to c$ transitions are predominantly left-handed [14]. However, we must recall that experimental measurements in $\bar{B} \to D^* l^-\nu_l$ decay assume that the lepton current is left-handed [14], but in our model leptons have both, left- and right-handed currents. (See the discussion in the last paragraph of Sec. IV.) More recently, also in $b \to X l \nu_l$ transitions, the dominant $(V - A) \times (V - A)$ structure of the weak charged currents has been confirmed. The maximal $(V + A) \times (V - A)$ is excluded with a significance of 5.7 and 3.7 standard deviations for the $b \to X e \nu_e$ and $b \to X \mu \nu_\mu$ cases, respectively. For the $b \to X e \nu_e$ the $V \times (V - A)$ structure is excluded by more than 3.5 standard deviations while for the $b \to X \mu \nu_\mu$ case it is found to be equally consistent with the $(V - A) \times (V - A)$ and the $V \times (V - A)$ case [19].

This does not exclude some right-handed current effects, for instance, by considering the four-fermion interaction for a semileptonic decay of $b$

$$2\sqrt{2}G_F V_{cb}[\langle \bar{c}_L \gamma^\mu b_L \rangle + \xi \langle \bar{c}_R \gamma^\mu b_R \rangle] \langle \bar{e}_L \gamma^\mu \nu_L \rangle, \quad (33)$$

with $\xi = g_R/g_L$, it has been shown that the difference of the value of $|V_{cb}|$ extracted from the total inclusive semileptonic decay rate of the $B$ mesons and the amplitude of the exclusive decay $B \to D^* l^-\nu_l$ is sensitive to an admixture of a right-handed $b \to c$ current. This can be interpreted in terms of the $\xi$ parameter in Eq. (33) and it has been found that $\xi \approx 0.14 \pm 0.18$ [20]. In the present model we have interactions like that in Eq. (33) if we consider Eq. (29) and the usual left-handed charged currents in the quark sector. However we also have right-handed charged currents in the lepton sector. If we neglect the last type of currents we can identify the $\xi$ parameter in Eq. (33) in terms of the right-handed mixing angles as follows:

$$\xi = \frac{|(V^P_R \Delta V^P_R)_{cb}|}{|V_{cb}|} \approx 0.14 \pm 0.18. \quad (34)$$

Hence, we see that there is room for such processes in this quasi-chiral model. There are $b$-decays induced by charged scalars too.

It is interesting to call attention to the fact that the measurement of the $\Lambda_b$ polarization gives $P_\Lambda = -0.23^{+0.24}_{-0.20}\text{(stat.)}^{+0.08}_{-0.07}\text{(syst.)}$ [21], while the value expected in the ESM is $P_\Lambda = -0.69 \pm 0.06$. (If right-handed currents do not exist this small polarization value indicates that there are new mechanisms for depolarization which still have to be understood.)

As it has been emphasized by Gronau and Wakaizumi [4] right-handed couplings of the $b$ quark to the $c$ and $u$ quarks would have effect in nonleptonic $b$ decays, extra contributions in $B^0_d - \bar{B}^0_d$ mixing, in the $K_L - K_S$ mass difference and in $CP$ violation. The study of $CP$ violation in $K$ and $B$ systems in the case of purely right-handed chirality for both $b$ to $c$ and $b$ to $u$ couplings has been done recently in Ref. [22].
In the previous discussion we have not considered the violation of the symmetry under $C P$. In the ESM we have in the charged current the mixing matrix $V_{\text{CKM}} = V_{L}^{U \dagger} V_{L}^{D}$ which is a unitary $n \times n$ matrix in the case of $n$ quark generations. It has $n^2 - n(n-1)/2$ phases after the unitarity conditions have been taking into account. On the other hand, even if the quarks are already the mass eigenstates we have freedom for absorbing a phase into each left-handed field: $u_{\alpha L} \rightarrow e^{i f(u_{\alpha})} u_{\alpha L}$ and $d_{\alpha L} \rightarrow e^{i f(d_{\alpha})} d_{\alpha L}$ (where $u_{\alpha L} = u_{L}, c_{L}, t_{L}, ...$ and $d_{\alpha L} = d_{L}, s_{L}, b_{L}, ...$) which removes the arbitrary phase from one row or column of $V_{\text{CKM}}$. But as this matrix is unchanged by a common phase transformation of all $u_{iL}$, only $2n - 1$ phase degrees of freedom can be removed in this way. Therefore the $V_{\text{CKM}}$ matrix has only $(n-2)(n-1)/2$ physically independent phases. This counting of the physical phases is possible only in the context of the ESM: the new phases in the left-handed fields are absorbed into the right-handed fields in the mass term and in the neutral current $u_{\alpha R} \rightarrow e^{i f(u_{\alpha})} u_{\alpha R}$ (similarly in the $d$-like right-handed components). Since these neutral currents are helicity and flavor conserving and the mass matrices have been already diagonalized, only $(n-2)(n-1)/2$ phases survive in the charged current. The other phases (and right-handed mixing matrices) will not appear at all in any place of the Lagrangian density.

On the other hand, in quasi-chiral models, as the present one, there are nondiagonal right-handed currents in both, charged and neutral currents. So we have no freedom to redefine the right-handed fields. Hence, the number of phases in the $V_{\text{CKM}}$ matrix is now $n^2 - n(n-1)/2 - 1$ since we have still freedom for choosing a common phase in all left- and right-handed fields. For $n = 3$ we have 4 phases instead of only one as in the ESM. We of course, can still insist in absorbing the phases in $V_{\text{CKM}}$ but the extra phases will appear in other places of the Lagrangian density. We have in this case for instance

$$V_{L}^{U \dagger} \Omega_{R}^{U} \rightarrow K^{u \dagger} V_{L}^{U \dagger} \Omega_{R}^{U} K^{u}, \quad V_{L}^{D \dagger} \Omega_{R}^{D} \rightarrow K^{d \dagger} V_{L}^{D \dagger} \Omega_{R}^{D} K^{d}, \quad V_{L}^{D \dagger} \Delta_{R}^{U} \rightarrow K^{d \dagger} V_{L}^{D \dagger} \Delta_{R}^{U} K^{u},$$

(35a)

in Eq. (9) and

$$V_{R}^{D \dagger} \Delta_{D}^{R} \rightarrow K^{d \dagger} V_{R}^{D \dagger} \Delta_{D}^{R} K^{d}, \quad V_{R}^{U \dagger} \Delta_{D}^{U} \rightarrow K^{u \dagger} V_{R}^{U \dagger} \Delta_{D}^{U} K^{u},$$

(35b)

in Eqs. (18) and (19), respectively; also

$$V_{R}^{U \dagger} \Delta_{D}^{R} \rightarrow K^{u \dagger} V_{R}^{U \dagger} \Delta_{D}^{R} K^{u},$$

(35c)

in Eq. (20), we have defined

$$K^{u} = \text{diag}(e^{i f(u_{1})}, e^{i f(u_{2})}, e^{i f(u_{3})}), \quad K^{d} = \text{diag}(e^{i f(d_{1})}, e^{i f(d_{2})}, e^{i f(d_{3})}).$$

(35d)

This makes richer the phenomenology of the present model. For instance, there are new phases in the non-diagonal neutral currents coupled to $Z^0$ as it is evident from Eqs. (18), (19) and (35b) and also in the right-handed current as can be seen from Eqs. (20) and (35c).

Summarizing, we have shown that it is possible to have (non-dominant) right-handed current effects in the context of a $SU(2) \otimes U(1)_Y$ model. These effects depend on the parameters $V_{L,R}^{U,D,I}$ which do not survive as observable parameters in the model when all generations transform in the same way i.e., as left-handed doublets and right-handed singlets.
Notwithstanding, we recall that the possibility that all the three families transform in a vector-like way is inconsistent with the present data. The charged currents given in Eq. (20) may still be phenomenological consistent since they involve the right-handed Cabibbo-like mixing matrix $V_R^{-U} \Delta V_R^{-D}$, then the dominant $V-A$ character of the charged weak interactions implies constraints only on these matrix elements. However, in this case the right-handed neutral current couplings, see Eqs. (18) and (19), are all proportional to $R_Q - 1$, $Q = U, D$, and this is in fact ruled out by currently $Z$-pole observables. On the other hand, it is still possible that two families transform in a vector-like way. The $\Delta$ in Eqs. (18)-(20) is in this case $\Delta \rightarrow \Delta' = diag(0, 1, 1)$. Of course, if we naively assume from the beginning that $V_R^{U,D,l} \approx 1$ the model is not consistent with data. It is necessary to assume that all these right-handed mixing matrices must be determined only by experiments.

We would like to stress once more that, all parameters appearing in the present model do exist in the electroweak standard model (here we have called it ESM) but the GIM mechanism [1] cancels out all of them in the Lagrangian density except three angles and one phase. Hence, here we have not introduced new parameters but we only have shown that in the quasi-chiral model (and this will occur also in other extensions of the ESM with flavor changing neutral currents) some of the parameters of the ESM do survive when we write the Lagrangian density in terms of the physical fields and even after absorbing all phases allowed by the interactions.

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