Flavor violation in a left-right model with mirror fermions

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Abstract: We study the conditions under which flavour violation arises in a left-right mirror model that includes additional fermions with mirror propierties for vector and scalar interactions.

1. Introduction

Recently several models involving mirror fermions generations, i.e., fermions with "mirror" isospin charges in a left-right symmetric context, have been presented. A first especulation for the existence of mirror fermions appeared in the classical paper on parity violation that led to the V-A interactions models [1]. Such a gauge group and fermions extensions, apart from fitting nicely into unification schemata, restores the left-right symmetry missing in the Standard Model (SM) in a manner that goes beyond the simplest left-right symmetry models.

In general, left-right symmetric models renders the baryon-lepton number symmetry $U(1)_{B-L}$ more natural by gauging it, and it has also been proposed as a solution to the strong CP problem when accompanied with the introduction of mirror fermions [3, 4]. Mirror fermions are very interesting objects from a phenomenological point of view and the low-energy effects have been studied [2, 5], existing limits on their masses have been presented too [?]. In addition to direct production, these new fermions can manifest themselves through their mixing with the known fermions, which can have effects in several aspects of flavour physics.

In this paper we analyze (Tree-level) family-changing neutral current (FCNC) interactions and lepton-flavor-violating (LFV) in a mirror model with gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$. The FCNC interactions are generally present in most of the extensions of the SM like Supersymmetry, Tecnicolor, etc.; in our model we can identify the flavour-changing transitions from three possible sources, namely: the exchange of family-changing neutral gauge bosons, the mixing between mirror and ordinary fermions, and the Higgs sector in the model.

The section 2 presents the fundamental aspects of the simplest LRMM model that solves the strong CP problem and it describes how the mixing effects modify the diagonal couplings generating FCNC and the conditions under which it appears.

2. Full Lagrangian

In the left-right model with mirror fermions (LRMM) [5], the right-handed (left-handed) components of mirror fermions transform as doublets (singlets) under $SU(2)_R$. The SM fermions are singlets under $SU(2)_R$, whereas the right-handed mirror are also singlets under $SU(2)_L$. Mirror and SM fermions will share hypercharge and color interactions. Thus, the first family of leptons and quarks will be

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written as follows:

$$\mathrm{l^o_{eL}} = \begin{pmatrix} \nu^o_e \\ e^o \end{pmatrix}_L, e^o_R, \hat{l}^o_{eR} = \begin{pmatrix} \hat{\nu}^o_e \\ \hat{e}^o \end{pmatrix}_R, \hat{e}^o_L \tag{2.1}$$

$$q^o_L = \begin{pmatrix} u^o \\ d^o \end{pmatrix}_L, u^o_R, d^o_R, \hat{q}^o_R = \begin{pmatrix} \hat{u}^o \\ \hat{d}^o \end{pmatrix}_R, \hat{u}^o_L, \hat{d}^o_R \tag{2.2}$$

The superscript (o) denote weak eigenstates, and the caret is associated with mirror particles. Similar terms can be written for the other families. Because the model does not contain left-handed mirror neutrinos, they have to be massless.

2.1 Symmetry Breaking

The symmetry breaking is realized by including two Higgs doublets, the SM one (ϕ) and its mirror partner $(\hat{\phi})$. The potential of the model can be written in a such a way that the vacuum expectation values (VEV's) of the Higgs field are

$$\langle\phi\rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathrm{v} \end{pmatrix}, \qquad \langle\hat{\phi}\rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{\mathrm{v}} \end{pmatrix}. \tag{2.3}$$

The most general potential consistent with Parity (P) symmetry that develops this VEV's is:

$$V = -\left(\lambda_1 \phi^\dagger\phi + \hat{\lambda_1}\hat{\phi}^\dagger\hat{\phi}\right) + \tfrac{\lambda_2}{2}\left[\left(\phi^\dagger\phi\right)^2 + \left(\hat{\phi}^\dagger\hat{\phi}\right)^2\right] + \lambda_3\left(\phi^\dagger\phi\right)\left(\hat{\phi}^\dagger\hat{\phi}\right). \tag{2.4}$$

In relation with the only one value λ_2 in the second factor may be we should mention that this choice arises because we put by hand parity breaking through dim-2 mass terms in Higgs potential.

The neutral Higgs boson square mass matrix that can be obtained from this potential is:

$$\mathsf{M}^2_{\mathsf{H}^0} = \begin{pmatrix} 2\lambda_1 v^2 & 2\lambda_2 v\hat{v} \\ 2\lambda_2 v\hat{v} & 2\lambda_1 \hat{v}^2 \end{pmatrix} \tag{2.5}$$

Diagonalization of the higgs-boson squared mass matrix is straightforward using a real basis. Out of the eight scalar degrees of freedom associated with two complex doublets, six become the Goldstone bosons required to give mass to $W^\pm$, $\hat{W}^\pm$, Z and $\hat{Z}$; thus only two neutral Higgs bosons remain; then neutral physical states are:

$$\begin{aligned} H &= \sqrt{2}\left[(\Re e\phi^o - \mathrm{v})\cos\alpha + \left(\Re e\hat{\phi}^o - \hat{\mathrm{v}}\right)\sin\alpha\right], \\ \hat{H} &= \sqrt{2}\left[(\mathrm{v} - \Re e\phi^o)\sin\alpha - \left(\hat{\mathrm{v}} - \Re e\hat{\phi}^o\right)\cos\alpha\right] \end{aligned} \tag{2.6}$$

where α is the mixing angle.

The mass matrix for the gauge bosons is obtained from the scalar Lagrangian

$$\mathcal{L}_{\mathrm{esc}} = \left(\mathrm{D}^\mu\phi\right)^\dagger\left(\mathrm{D}_\mu\phi\right) + \left(\hat{\mathrm{D}}^\mu\hat{\phi}\right)^\dagger\left(\hat{\mathrm{D}}_\mu\hat{\phi}\right) \tag{2.7}$$

where D_μ denotes the covariant derivative associated with the SM, and $\hat{D}_\mu$ is the one associated with the mirror part.

After the substitution of the VEV's in the Lagrangian we obtain the expressions for the mass matrices. The mass matrix for the charged gauge bosons is already diagonal, with mass eigen-values: $M_W = \frac{1}{2}vg$ and $M_{\hat{W}} = \frac{1}{2}\hat{v}\hat{g}$, where g and $\hat{\mathrm{g}}$ are the coupling constant associated with the $SU(2)_{\mathrm{L}}$ and $SU(2)_{\mathrm{R}}$ gauge group, respectively. The mass matrix for the neutral gauge bosons is not diagonal, and it has one massless and two massive eigenvalues

$$\begin{aligned} M_{\mathrm{Z,Z'}} &= \tfrac{1}{2}\left[v^2\left(g^2 + g'^2\right) + \hat{v}^2\left(\hat{g}^2 + g'^2\right)\right] \\ &\mp \tfrac{1}{2}\begin{pmatrix} \left[v^2\left(g^2 + g'\right) + \hat{v}^2\left(\hat{g}^2 + g'^2\right)\right]^2 \\ -4v^2\hat{v}^2\left(g^2 g'^2 + g^2\hat{g}^2 + \hat{g}^2 g'^2\right) \end{pmatrix}^{1/2} \end{aligned} \tag{2.8}$$

where g' is the coupling constant of the $U(1)$ gauge group, the matrix can be diagonalized by an orthogonal transformation R, relating the weak and mass eigenstates, given by [5]

$$\mathrm{R} = \begin{pmatrix} c_{\theta_w} c_\Theta & c_{\theta_w} s_\Theta & s_{\theta_w} \\ -\frac{1}{c_{\theta_w}}\begin{pmatrix} s_\Theta r_{\theta_w} + \\ \frac{\mathrm{g}}{\hat{\mathrm{g}}} c_\Theta s^2_{\theta_w} \end{pmatrix} & \frac{1}{c_{\theta_w}}\begin{pmatrix} c_\Theta r_{\theta_w} - \\ \frac{\mathrm{g}}{\hat{\mathrm{g}}} s_\Theta s^2_{\theta_w} \end{pmatrix} & \frac{\mathrm{g}}{\hat{\mathrm{g}}} s_{\theta_w} \\ t_{\theta_w}\begin{pmatrix} \frac{\mathrm{g}}{\hat{\mathrm{g}}} s_\Theta - \\ r_{\theta_w} c_\Theta \end{pmatrix} & -t_{\theta_w}\begin{pmatrix} \frac{\mathrm{g}}{\hat{\mathrm{g}}} c_\Theta + \\ r_{\theta_w} s_\Theta \end{pmatrix} & r_{\theta_w} \end{pmatrix}, \tag{2.9}$$

with θ_w and Θ the rotations angles between the Z -A and Z - Z′ gauge bosons, respectively. In the eq. (2.9), $r_{\theta_w} \equiv \sqrt{c^2_{\theta_w} - \frac{\mathrm{g}^2}{\hat{\mathrm{g}}^2} s^2_{\theta_w}}$.

In order to find the couplings of the Higgs fields from eq. (2.7), we use the expressions for

D_μ and $\hat{D}_\mu$, substituting the physical states. For the Z-H-$\hat{H}$ Higgs interactions we get

$$\mathcal{L}_{\mathrm{ZZ\hat{H}}} = \sqrt{2}\begin{pmatrix} \mathrm{gM_W X}(\Theta,\theta_\mathrm{w})\cos\alpha + \\ \hat{\mathrm{g}}M_{\hat{W}}Y(\Theta,\theta_\mathrm{w})\sin\alpha \end{pmatrix}\mathrm{HZ_\mu Z^\mu} + \sqrt{2}\begin{pmatrix} -\mathrm{gM_W X}(\Theta,\theta_\mathrm{w})\sin\alpha + \\ \hat{\mathrm{g}}M_{\hat{W}}Y(\Theta,\theta_\mathrm{w})\cos\alpha \end{pmatrix}\hat{\mathrm{H}}\mathrm{Z_\mu Z^\mu} \quad (2.10)$$

where

$$\mathrm{X}(\Theta,\theta_\mathrm{w}) = \left[\mathrm{c}_{\theta_\mathrm{w}}\mathrm{c}_\Theta - \frac{\mathrm{g}'}{\mathrm{g}}\mathrm{t}_{\theta_\mathrm{w}}\left(\frac{\mathrm{g}}{\hat{\mathrm{g}}}\mathrm{s}_\Theta - \mathrm{r}_{\theta_\mathrm{w}}\mathrm{c}_\Theta\right)\right]^2, \quad (2.11)$$

$$\mathrm{Y}(\Theta,\theta_\mathrm{w}) = \begin{bmatrix} -\frac{1}{c_{\theta_w}}\left(s_\Theta r_{\theta_w} + \frac{g}{\hat{g}}c_\Theta s^2_{\theta_w}\right) - \\ \frac{g'}{g}t_{\theta_w}\left(\frac{g}{\hat{g}}s_\Theta - r_{\theta_w}c_\Theta\right) \end{bmatrix}^2 \quad (2.12)$$

and for the W-W-$\hat{H}$ interactions the result is

$$\mathcal{L}_{\mathrm{WH\hat{H}}} = \sqrt{2}\mathrm{gM_W g}^{\mu\nu}\left(\mathrm{H}\cos\alpha - \hat{\mathrm{H}}\sin\alpha\right)\mathrm{W}^-_\mu\mathrm{W}^+_\nu \quad (2.13)$$

2.2 Yukawa Lagrangian and fermion mixing

The gauge interaction of quarks and leptons can be obtained from the generic Lagrangian

$$\mathcal{L}^{\mathrm{int}} = \overline{\psi}\mathrm{i}\gamma^\mu\mathcal{D}^\mu\psi + \overline{\hat{\psi}}\mathrm{i}\gamma^\mu\hat{\mathcal{D}}_\mu\hat{\psi} \quad (2.14)$$

where ψ, $\hat{\psi}$ denote the standard and mirror fermions, respectively.

To consider the mixing of fermions, including the mirror ones, we follow Ref. [7], grouping all fermions of a given electric charge q and a helicity $a = \mathrm{L,R}$ into $n_a + m_a$ vector column of n_a standard (s) and m_a mirror (m) gauge eigenstates, i.e. $\psi^o_a = (\psi^o_s, \psi^o_m)^\top_a$.

The relation between the gauge eigenstates and the corresponding light (l) and heavy (h) mass eigenstates $\psi_a = (\psi_l, \psi_h)^\top_a$ is given by a unitary transformation [1]

$$\psi^o_a = \mathsf{U}_a\psi_a \quad (2.15)$$

[1]We shall name the light fermions as the SM ones, although this is not strictly twe, then the heavy ones (ψ_h) will be consider the sector beyond the SM.

where

$$\mathsf{U}_a = \begin{pmatrix} \mathsf{A}_a & \mathsf{E}_a \\ \mathsf{F}_a & \mathsf{G}_a \end{pmatrix}. \quad (2.16)$$

From the unitarity of U

$$\left(\mathsf{U_a U_a^\dagger}\right) = 1. \quad (2.17)$$

its easy to see that the submatrix $\mathsf{A_a}$ is not unitary. The term $\left(\mathsf{F^\dagger F}\right)_a$, which is second order in the small mirror-standard fermion mixing, induce FC transitions in the light-light sector.

The renormalizable and gauge invariant interactions of the scalar doublets ϕ and $\hat{\phi}$ with the leptons are described by the Yukawa Lagrangian, and take the form

$$\mathcal{L}^{\mathrm{l}}_{\mathcal{Y}} = \sum_{\mathrm{i,j}}\lambda_{\mathrm{ij}}\overline{\mathrm{l}^{\mathrm{o}}_{\mathrm{iL}}}\phi\mathrm{e}^{\mathrm{o}}_{\mathrm{jR}} + \sum_{\mathrm{i,j}}\hat{\lambda}_{\mathrm{ij}}\overline{\hat{\mathrm{l}}^{\mathrm{o}}_{\mathrm{iL}}}\hat{\phi}\hat{\mathrm{e}}^{\mathrm{o}}_{\mathrm{jR}} + \sum_{\mathrm{i,j}}\mu_{\mathrm{ij}}\overline{\hat{\mathrm{e}}^{\mathrm{o}}_{\mathrm{iL}}}\mathrm{e}^{\mathrm{o}}_{\mathrm{jR}} + \mathrm{h.c.} \quad (2.18)$$

where $\mathrm{i,j} = 1,2,3$ and λ_{ij}, $\hat{\lambda}_{\mathrm{ij}}$, and μ_{ij} are unknown constants.

For the quarks fields, the corresponding Yukawa terms are written as

$$\begin{aligned}\mathcal{L}^{\mathrm{Q}}_{\mathcal{Y}} = &\sum_{\mathrm{i,j}}\lambda^{\mathrm{d}}_{\mathrm{ij}}\overline{\mathrm{Q}^{\mathrm{O}}_{\mathrm{iL}}}\phi\mathrm{D}^{\mathrm{o}}_{\mathrm{jR}} + \sum_{\mathrm{i,j}}\lambda^{\mathrm{u}}_{\mathrm{ij}}\overline{\mathrm{Q}^{\mathrm{o}}_{\mathrm{iL}}}\tilde{\phi}\mathrm{U}^{\mathrm{o}}_{\mathrm{jR}} + \\ &\sum_{i,j}\hat{\lambda}^{\mathrm{d}}_{\mathrm{ij}}\overline{\hat{\mathrm{Q}}^{\mathrm{o}}_{\mathrm{iR}}}\hat{\phi}\hat{\mathrm{D}}^{\mathrm{o}}_{\mathrm{jL}} + \sum_{\mathrm{ij}}\lambda^{\hat{\mathrm{u}}}_{\mathrm{ij}}\overline{\hat{\mathrm{Q}}^{\mathrm{o}}_{\mathrm{iR}}}\tilde{\hat{\phi}}\hat{\mathrm{U}}^{\mathrm{o}}_{\mathrm{jL}} + \\ &\sum_{\mathrm{i,j}}\mu^{\mathrm{d}}_{\mathrm{ij}}\overline{\hat{\mathrm{D}}^{\mathrm{o}}_{\mathrm{iL}}}\mathrm{D}^{\mathrm{o}}_{\mathrm{jR}} + \sum_{\mathrm{i,j}}\mu^{\mathrm{u}}_{\mathrm{ij}}\overline{\hat{\mathrm{U}}^{\mathrm{o}}_{\mathrm{iL}}}\mathrm{U}^{\mathrm{o}}_{\mathrm{jR}} + \mathrm{h.c}\end{aligned} \quad (2.19)$$

where the conjugate fields $\tilde{\phi}$ $(\tilde{\hat{\phi}})$ are obtained as $\tilde{\phi} = \mathrm{i}\tau_2\phi^*$.

The VEV's of the neutral scalars produces the mass terms, which in the gauge eigenstate basis reads

$$\mathcal{L}_{\mathrm{mass}} = \overline{\psi^{\mathrm{O}}_{\mathrm{L}}}\mathrm{M}\psi^{\mathrm{O}}_{\mathrm{R}} + \mathrm{h.c.} \quad (2.20)$$

The nondiagonal mass matrix M takes the form

$$\mathrm{M} = \begin{pmatrix} \mathsf{D} & 0 \\ \mu & \hat{\mathsf{D}} \end{pmatrix}, \quad (2.21)$$

where $\mathsf{D} = \frac{1}{2}\lambda\mathsf{v}$ and $\hat{\mathsf{D}} = \frac{1}{2}\hat{\lambda}\hat{v}$ corresponding to 3 x 3 matrices generated from the symmetry breaking VEV's , while μ corresponding to gauge invariant 3 x 3 mixing mass terms between ordinary and mirror fermions singlets.

The diagonal mass matrix $\mathrm{M_D}$ can be obtained through a biunitary rotation acting on the L and R sectors, namely:

$$\mathrm{M_D} = \mathsf{U}_\mathrm{L}^\dagger \mathrm{M} \mathsf{U}_\mathrm{R} \tag{2.22}$$

We will follow here the Ref. [8] to analysis of mixing effects, concentrating mainly on the charged fermions sector and on flavor-changing effects.

The neutral current term for the multiplet ψ of a given electric charge, including the contribution of the neutral gauge boson mixing, can be written as follows

$$-\mathcal{L}^{\mathrm{nc}} = \sum_{\mathrm{a=L,R}} \overline{\psi_\mathrm{a}^\mathrm{o}} \gamma^\mu \left(\mathrm{g T_{3a}}, \hat{\mathrm{g}} \hat{\mathrm{T}}_{\mathrm{3a}}, \mathrm{g}' \frac{\mathrm{Y_a}}{2} \right) \psi_\mathrm{a}^\mathrm{o} \begin{pmatrix} \mathrm{W}^3 \\ \hat{\mathrm{W}}^3 \\ \mathrm{B} \end{pmatrix}_\mu \tag{2.23}$$

In terms of the mass eigenstates, using eqs. (2.15, 2.16), one arrives to:

$$-\mathcal{L}^{\mathrm{nc}} = \sum_{\mathrm{a=L,R}} \overline{\psi_\mathrm{a}} \gamma^\mu \mathsf{U}_\mathrm{a}^\dagger \left(\mathrm{g T_{3a}}, \hat{\mathrm{g}} \hat{\mathrm{T}}_{\mathrm{3a}}, \mathrm{g}' \frac{\mathrm{Y_a}}{2} \right) \mathsf{U}_\mathrm{a} \psi_\mathrm{a} \mathrm{R} \begin{pmatrix} \mathrm{Z} \\ \mathrm{Z}' \\ \mathrm{A} \end{pmatrix}_\mu \tag{2.24}$$

where $\mathrm{T_{3a}}$, $\hat{\mathrm{T}}_{\mathrm{3a}}$, and Y are the generators of the $SU(2)_\mathrm{L}$, $SU(2)_\mathrm{R}$, and $U(1)$, respectively.

On the other hand, after substitute the expression for mass-eigenstates eq. (2.22), we can express parameters λ, $\hat{\lambda}$, and μ, in terms of the mass-eigenvalues and the blocks of matrix U, as follows

$$\lambda = \frac{\mathsf{g}}{\sqrt{2}} \left(\mathsf{A}_\mathrm{L} \frac{\mathsf{m_f}}{\mathsf{M_W}} \mathsf{A}_\mathrm{R}^\dagger + \mathsf{E}_\mathrm{L} \frac{\mathsf{m}_{\hat{\mathsf{f}}}}{\mathsf{M_W}} \mathsf{E}_\mathrm{R}^\dagger \right), \tag{2.25}$$

$$\hat{\lambda} = \frac{\hat{\mathsf{g}}}{\sqrt{2}} \left(\mathsf{F}_\mathrm{L} \frac{\mathsf{m_f}}{\mathsf{M}_{\hat{\mathsf{W}}}} \mathsf{F}_\mathrm{R}^\dagger + \mathsf{G}_\mathrm{L} \frac{\mathsf{m}_{\hat{\mathsf{f}}}}{\mathsf{M}_{\hat{\mathsf{W}}}} \mathsf{G}_\mathrm{R}^\dagger \right), \tag{2.26}$$

$$\mu = \mathsf{F}_\mathrm{L} \mathsf{m_f} \mathsf{A}_\mathrm{R}^\dagger + \mathsf{G}_\mathrm{L} \mathsf{m}_{\hat{\mathsf{f}}} \mathsf{E}_\mathrm{R}^\dagger, \tag{2.27}$$

$$0 = \mathsf{A}_\mathrm{L} \mathsf{m_f} \mathsf{F}_\mathrm{R}^\dagger + \mathsf{E}_\mathrm{L} \mathsf{m}_{\hat{\mathsf{f}}} \mathsf{G}_\mathrm{R}^\dagger \tag{2.28}$$

With help of these relations, and working within the Higgs mass-eigenstates basis, the tree-level interactions of the neutral Higgs bosons H and $\hat{H}$ with the light fermions are given by

$$\mathcal{L}_\mathrm{f} = \frac{\mathrm{g}}{2\sqrt{2}} \overline{\mathsf{f}_\mathrm{L}} \mathsf{A}_\mathrm{L}^\dagger \mathsf{A}_\mathrm{L} \frac{\mathrm{m_l}}{\mathcal{M}_\mathcal{W}} \{_\mathrm{R} \left(\mathrm{H} \cos\alpha - \hat{\mathrm{H}} \sin\alpha \right) + \frac{\hat{\mathrm{g}}}{2\sqrt{2}} \overline{\mathsf{f}_\mathrm{L}} \frac{\mathrm{m_l}}{M_{\hat{W}}} \mathsf{F}_\mathrm{R}^\dagger \mathsf{F}_\mathrm{R} f_\mathrm{R} \left(\mathrm{H} \sin\alpha + \hat{\mathrm{H}} \cos\alpha \right) + \mathrm{h.c.} \tag{2.29}$$

One can see that the couplings are not diagonal in general, thus new phenomena associated with FCNC will be predicted in this model. The resulting phenomenological constraints and predictions will be discussed in future work [9].

For instance, once we obtain bounds on the coefficients of the couplings $\phi l_i l_j$, we can use these results to predict the Branching Ratio for the LFV decay modes of the Higgs themselves, namely $\mathrm{H} \to \mu e$, $\tau\mu$, τe, which could be detected at the future colliders (Tevatron and LHC).

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