Phenomenology of the $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ model with right-handed neutrinos

D.A. Gutiérrez$^1$, W.A. Ponce$^1$, L.A. Sánchez$^{2,a}$

$^1$ Instituto de Física, Universidad de Antioquia, A.A. 1226, Medellín, Colombia
$^2$ Escuela de Física, Universidad Nacional de Colombia, A.A. 3840, Medellín, Colombia

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Abstract. A phenomenological analysis of the three-family model based on the local gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ with right-handed neutrinos is carried out. Instead of using the minimal scalar sector able to break the symmetry in a proper way, we introduce an alternative set of four Higgs scalar triplets, which combined with an anomaly-free discrete symmetry, produces a quark mass spectrum without hierarchies in the Yukawa coupling constants. We also embed the structure into a simple gauge group and show some conditions for achieving a low energy gauge coupling unification, avoiding possible conflict with proton decay bounds. By using experimental results from the CERN-LEP, SLAC linear collider, and atomic parity violation data, we update constraints on several parameters of the model.

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1 Introduction

Two intriguing puzzles completely unanswered in modern particle physics are the number of fermion families in nature, and the pattern of masses and mixing angles in the fermion sector. One interesting attempt to answer to the question of family replication is provided by the 3-3-1 extension of the local gauge symmetry $SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$ of the standard model (SM) of the strong and electroweak interactions [1]. This extension, based on the local gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, has among its best features that several models can be constructed so that anomaly cancellation is achieved by an interplay between the families, all of them under the condition $N_f = N_c = 3$, where $N_f$ is the number of families and $N_c$ is the number of colors of $SU(3)_c$ (three-family models) [2].

Two 3-3-1 three-family models have been extensively studied over the last decade [2,3]. In one of them, the three known left-handed lepton components for each family are associated to three $SU(3)_L$ triplets as $(\nu_l, l^-, l^+)_L$, where $l^+_R$ is related to the right-handed isospin singlet of the charged lepton $l^-_R$ in the SM [2]. In the other model, the three $SU(3)_L$ lepton triplets are of the form $(\nu_l, l^-, \nu^c_l)_L$, where $\nu^c_l$ is related to the right-handed component of the neutrino field $\nu_l$ (a model with right-handed neutrinos) [3]. In the first model, anomaly cancellation implies quarks with the exotic electric charges $-4/3$ and $5/3$, while in the second one the extra particles have only ordinary electric charges.

Our aim in this paper is to do a phenomenological analysis of the 3-3-1 model in the version that includes right-handed neutrinos, including a detailed study of the fermion mass spectrum, with emphasis in the quark sector. Previous work [3] just presented the Yukawa Lagrangians without looking for constraints able to produce a consistent quark mass spectrum. It will be shown that a convenient set of four Higgs scalars, combined with an appropriate anomaly-free discrete $Z_2$ symmetry, produces an appealing quark mass spectrum without strong hierarchies for the Yukawa couplings. Furthermore, we shall study the embedding and unification of this gauge structure into $SU(6)$, which is an appropriate unification gauge group. Finally, we will set updated constraints on several parameters of the model.

The problem of lepton masses in the context of 3-3-1 three-family models has been studied, for example, in [4,5], and we already know, from the analysis presented in [5–7], that models based on the 3-3-1 local gauge structure are suitable for describing some neutrino properties, because they include in a natural way most of the ingredients needed to explain the masses and mixing in the neutrino sector. In particular, [6] addresses this issue for the model studied here.

This paper is organized as follows. In Sect. 2 we review the model, introduce the new scalar sector, embed the structure into a covering group and calculate the charged and neutral electroweak currents. In Sect. 3 we study the charged fermion mass spectrum. In Sect. 4 we do the renormalization group equation analysis and show the conditions for the gauge coupling unification. In Sect. 5 we fix

* e-mail: lasanche@unalmed.edu.co
the new bounds on the mixing angle between the two flavor diagonal neutral currents present in the model, and discuss the constraints coming from violation of the unitarity of the Cabbibo–Kobayashi–Maskawa (CKM) quark-mixing matrix and from flavor changing neutral currents (FCNC). Finally, in the last section, we present our conclusions.

2 The model

The model that we are about to study here was sketched for the first time in the literature in the first reference in [3], with some phenomenology presented in the other four papers in the same reference. Some of the formulas quoted in the following sections are taken from those references and from [8]; corrections to some minor printing mistakes in the original papers are included.

2.1 The gauge group

As was stated above, the model that we are interested in is based on the local gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, which has 17 gauge bosons: one gauge field $B^\mu$ associated with $U(1)_X$, the eight gluon fields $G^\mu$ associated with $SU(3)_c$, which remain massless after breaking the symmetry, and another eight gauge fields associated with $SU(3)_L$ and for convenience written as [8]

$$\frac{1}{2} \lambda_\alpha A^\mu_\alpha = \frac{1}{\sqrt{2}} \begin{pmatrix} D^\mu_+ W^{+\mu} K^{+\mu} \\ D^\mu_- W^{-\mu} D^\mu_0 K^{0\mu} \\ K^{-\mu} K^{0\mu} D^\mu_3 \end{pmatrix} ,$$

where $D^\mu_+ = A^\mu_+/\sqrt{2}$, $D^\mu_- = -A^\mu_- \sqrt{2}$, and $D^\mu_3 = -A^\mu_3 \sqrt{6}$. The matrices normalized as $Tr(\lambda_\alpha \lambda_\beta) = 2 \delta_{\alpha\beta}$.

The charge operator associated with the unbroken gauge symmetry $U(1)_Q$ is given by

$$Q = \frac{\lambda_{3L}}{2} + \frac{\lambda_{SL}}{2\sqrt{3}} + X I_3 ,$$

where $I_3 = \text{diag}(1,1,1)$ is the diagonal $3 \times 3$ unit matrix, and the $X$ values are related to the $U(1)_X$ hypercharge and are fixed by anomaly cancellation. The sine square of the electroweak mixing angle is given by

$$S^2_W = 3g_1^2/(3g_3^2 + 4g_1^2) ,$$

where $g_1$ and $g_3$ are the gauge coupling constants of $U(1)_X$ and $SU(3)_L$, respectively, and the photon field is given by [3, 8]

$$A^\mu_W = S_W A^\mu_3 + C_W \left[ \frac{T_W}{\sqrt{3}} A^\mu_8 + \sqrt{1 - T_W^2/3} B^\mu \right] ,$$

where $C_W$ and $T_W$ are the cosine and tangent of the electroweak mixing angle, respectively.

There are two weak neutral currents in the model associated with the two flavor diagonal neutral weak gauge bosons

$$Z^\mu_0 = C_W A^\mu_3 - S_W \left[ \frac{T_W}{\sqrt{3}} A^\mu_8 + \sqrt{1 - T_W^2/3} B^\mu \right] ,$$

$$Z^\mu_0 = - \sqrt{(1 - T_W^2/3)} A^\mu_8 + \frac{T_W}{\sqrt{3}} B^\mu ,$$

and one associated with the flavor nondiagonal electrically neutral gauge boson $K^{0\mu}$, which carries a kind of weak V-isospin charge. In the former expressions, $Z^\mu_0$ coincides with the weak neutral current of the SM [3, 8]. Using (3) and (4), we realize that the gauge boson $Y^\mu$ associated with the abelian hypercharge in the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ SM gauge group is

$$Y^\mu = \frac{T_W}{\sqrt{3}} A^\mu_8 + \sqrt{1 - T_W^2/3} B^\mu .$$

2.2 The spin 1/2 particle content

The quark content for the three families in this model (known in the literature as the 3-3-1 model with right-handed neutrinos) is the following: $Q^i_L = (u^i, d^i, D^i)_L \sim (3, 3, 0), i = 1, 2$ for two families, where $D^i_L$ are two extra quarks of electric charge $1/3$ (the numbers in parentheses stand for the $[SU(3)_c, SU(3)_L, U(1)_X]$ quantum numbers in that order); $Q^3_L = (d^3, u^3, U^3)_L \sim (3, 3^*, 1, 3)$, where $U^3_L$ is an extra quark of electric charge $2/3$. The right-handed quarks are $u^a_L \sim (3^*, 1, -2/3), d^a_L \sim (3^*, 1, 1/3)$ with $a = 1, 2, 3$ being a family index, $D^i_L \sim (3^*, 1, 1/3), i = 1, 2$, and $U^a_L \sim (3^*, 1, -2/3)$.

The lepton content is given by the three $SU(3)_L$ antitriplets $\bar{L}^l_L = (l^-, \nu^l, \nu^l_3) L \sim (1, 3^*, -1/3)$, for $l = e, \mu, \tau$ a leptonic family index, and the three singlets $l^l_0 \sim (1, 1, 1), \nu^l_0$ the neutrino field associated with the lepton $l^-$, and $\nu^l_3$ plays the role of the right-handed neutrino field associated to the same flavor. Notice that this model does not contain exotic charged leptons, and universality for the known leptons in the three families is present at the tree-level in the weak basis.

With these quantum numbers it is just a matter of counting to check that the model is free of the following gauge anomalies [8]: $[SU(3)_c]_3^3$ (as in the SM, $SU(3)_c$ is vector-like); $[SU(3)_L]_3^3$ (six triplets and six antitriplets), $[SU(3)_c]_2 U(1)_X$; $[SU(3)_L]_2 U(1)_X$; $[\text{grav}]^2 U(1)_X$ and $[U(1)_X]_3^3$, where $[\text{grav}]^2 U(1)_X$ stands for the gravitational anomaly as described in [9].

2.3 The new scalar sector

Instead of using the set of three triplets of Higgs scalars introduced in the original papers [3], or the most economical set of two triplets introduced in [8] (none of them being able to produce a realistic mass spectrum), we propose here