Possibilities beyond 3-3-1 models

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We consider generalizations of the standard model (SM) which are based on the gauge symmetry $SU(n_c) \otimes SU(m)_L \otimes U(1)_N$. Although the most interesting possibilities occur when $n = 3$, we will consider also the cases $n = 4, 5$ both with $m = 3, 4$. Models with left-right symmetry, horizontal symmetries and the possible embedding in a larger group (grand unification scenarios) are briefly discussed.

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I. INTRODUCTION

Recently, a class of $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ models was considered in Refs. \cite{1,2} with several representation contents (called 3-3-1 models by Frampton Ref. \cite{1}.) Such models are anomaly free only if there is equal number of triplets and antitriplets (considering the color degrees of freedom), and furthermore requiring the sum of all fermion charges to vanish. Two of the three quark generations transform identically and one generation, it does not matter which \cite{1}, transforms in a different representation of $SU(3)_L \otimes U(1)_N$. This means that in these models, which are undistinguishable from the standard model at low energies, in order to cancel anomalies, the number of families ($N_f$) must be divisible by the number of color degrees of freedom ($n$). Hence the simplest alternative is $n = N_f$. Another interesting feature of these models is that the weak mixing angle of the standard model has an upper limit. For instance, in the model of Refs. \cite{1} $\sin^2 \theta_W$ has to be smaller than $1/4$. Therefore, it is possible to compute an upper limit to the mass scale of the $SU(3)$ breaking of about 1.7 TeV \cite{3}. This makes 3-3-1 models interesting possibilities for the physics beyond the standard model. Hence, it is also interesting to study how the basic ideas of this sort of models can be generalized.

Here we want to generalize this models in several ways: by expanding the color degrees of freedom ($n$) and the electroweak sector ($m$), i.e., we will consider models based on the gauge symmetry

$$SU(n)_c \otimes SU(m)_L \otimes U(1)_N. \quad (1.1)$$

In all these extensions the anomaly cancellation occurs among all generations together, and not generation per generation. Models with left-right symmetry and/or with horizontal symmetry are also considered. We discuss too possible grand unified theories in which some of these models may be embedded.

We will use the criterion that the values for $m$ are determined by the leptonic sector. In the color sector for simplicity, in addition to the usual case of $n = 3$, we will comment the
cases $n = 4, 5$. These extensions have been considered in the context of the $SU(2)_L \otimes U(1)_Y$ model \cite{3,7}.

This work is organized as follows. In Sec.II we will consider models with $n = 3, m = 3, 4$ (Sec.IIA). There we will also discuss the cases when $n = 4, 5$ (Sec.IIB). In Sec.III we will give general features of the extensions with left-right symmetry (Sec.IIIA) and with horizontal symmetries (Sec.IIIB). We also consider (Sec.IIC) possible embedding in $SU(6)$. The last section is devoted to our conclusions.

II. MODELS WITH EXTENDED COLOR AND ELECTROWEAK SECTORS

A. Models with extended electroweak sector

First, let us consider the $n = 3$ models. In this case, $m = 2$ gives the standard model. The case of $m = 3$ is possible with three leptons belonging to the fundamental representation of $SU(3)_L$. As this kind of models has been already considered in detail in Refs. \cite{1,2,3} here we will treat them briefly. Consider leptons transforming as triplets $(3, 0)$ under $SU(3)_L \otimes U(1)_N$: $(\nu_a, l_a, l^c_a)_L$, where $a = 1, 2, 3$ is the family index and $l^c_a$ are the charge conjugate fields. In this model there are, besides the usual quarks of the standard model, three exotic ones with charges $\frac{5}{3}$ (one) and $-\frac{4}{3}$ (two). It means that there are nine quarks, each one with the three usual color degrees of freedom. It is also possible the following representation content $(\nu^c_a, \nu_a, l^c_a)_L \sim (3^*, -1/3)$, and it is necessary to introduce new quarks with the same charge of the known quarks. The model has also 9 quarks, four of them with charge $2/3$ and five with charge $-1/3$ \cite{2,8}. Let us write down explicitly the quark content since this model will be considered in Sec. III C. The first and second “generations” are in triplets $(3, 0)$, and the third one in an antitriplet $(3^*, 1/3)$ \cite{9}:

$$Q_{iL} = \begin{pmatrix} u_i \\ d_i \\ d^c_i \end{pmatrix}_L \sim (3, 0), \quad i = 1, 2; \quad Q_{3L} = \begin{pmatrix} t' \\ t \\ b \end{pmatrix}_L \sim (3^*, 1/3).$$

(2.1)
All right-handed charged fermions are taken to be $SU(3)$ singlets. The representations above are in terms of symmetry eigenstates.

Next, we consider an example of a 3-4-1 model in which the electric charge operator is defined as

$$Q = \frac{1}{2}(\lambda_3 - \frac{1}{\sqrt{3}}\lambda_8 - \frac{2}{3}\sqrt{6}\lambda_{15}) + N,$$

where the $\lambda$-matrices are a slightly modified version of the usual ones [10],

$$\lambda_3 = diag(1, -1, 0, 0), \quad \lambda_8 = (\frac{1}{\sqrt{3}})diag(1, 1, -2, 0), \quad \lambda_{15} = (\frac{1}{\sqrt{6}})diag(1, 1, 1, -3).$$

Leptons transform as $(1, 4, 0)$, two of the three quark families, say $Q_{iL}, i = 2, 3$, transform as $(3, 4^*, -1/3)$, and one family, $Q_{1L}$, transforms as $(3, 4, +2/3)$

$$\psi_{aL} \sim \begin{pmatrix} \nu_a \\ l_a \\ \nu^c_a \\ l^c_a \end{pmatrix}_L, \quad Q_{4L} \sim \begin{pmatrix} u_1 \\ d_1 \end{pmatrix}_L, \quad Q_{1L} \sim \begin{pmatrix} j_i \\ d'_i \\ u_i \end{pmatrix}_L,$$

where $u'_1$ and $J$ are new quarks with charge $+2/3$ and $+5/3$ respectively; $j_i$ and $d'_i, i = 2, 3$ are new quarks with charge $-4/3$ and $-1/3$ respectively. We remind that in Eq. (2.3) all fields are still symmetry eigenstates. Right-handed quarks transform as singlets under $SU(4)$.

A model with $SU(4)_L$ symmetry and leptons transforming as in Eq. (2.3) was proposed by Voloshin some years ago [11]. In this context it can be possible to understand the existence of neutrinos with large magnetic moment and small mass. However in Ref. [11] it was not considered the quark sector.

Quark masses are generated by introducing the following Higgs $SU(4)_L \otimes U(1)_N$ multiplets: $\chi \sim (4, +1), \rho \sim (4, +1/3), \eta$ and $\eta' \sim (4, 0)$.

In order to obtain massive charged leptons it is necessary to introduce a $(10^*, 0)$ Higgs multiplet, because the lepton mass term transforms as $\bar{\psi}_L^c \psi_L \sim (6_A \oplus 10_S)$. The $6_A$ will leave some leptons massless and some others mass degenerate. Therefore we will choose $H = 10_S$. 

4
Neutrinos remain massless at least at tree level but the charged leptons gain mass. The corresponding VEVs are the following

\[ \langle \eta \rangle = (v, 0, 0, 0) \]
\[ \langle \rho \rangle = (0, w, 0, 0) \]
\[ \langle \eta' \rangle = (0, 0, v', 0) \]
\[ \langle \chi \rangle = (0, 0, 0, u) \]
\[ \langle H \rangle_{42} = v'' \]

for the decuplet. In this way we have that the symmetry breaking of the \( SU(4)_L \otimes U(1)_N \) group down to \( SU(3)_L \otimes U(1)_{N'} \) is induced by the \( \chi \) Higgs. The \( SU(3)_L \otimes U(1)_{N'} \) symmetry is broken down into \( U(1)_{em} \) by the \( \rho, \eta, \eta' \) and \( H \) Higgs.

As in the model I of Ref. [2], it is necessary to introduce some discrete symmetries which ensure that the Higgs fields give a quark mass matrix in the charge \(-1/3\) and \(2/3\) sectors of the tensor product form in order to avoid general mixing among quarks of the same charge. In this case the quark mass matrices can be diagonalized with unitary matrices which are themselves tensor product of unitary matrices.

In fact, we have the symmetry breaking pattern, including the \( SU(3) \) of color,

\[
\begin{align*}
SU(3)_c & \otimes SU(4)_L \otimes U(1)_N \\
\downarrow & \langle \chi \rangle \\
SU(3)_c & \otimes SU(3)_L \otimes U(1)_{N'} \\
\downarrow & \langle \eta' \rangle \\
SU(3)_c & \otimes SU(2)_L \otimes U(1)_{N''} \\
\downarrow & \langle x \rangle \\
SU(3)_c & \otimes U(1)_{em}
\end{align*}
\]

where \( \langle x \rangle \) means \( \langle \rho \rangle, \langle \eta \rangle, \langle H \rangle \) [12].

The electroweak gauge bosons of this theory consist of a 15 \( W^i \mu, i = 1, ..., 15 \) associated with \( SU(4)_L \) and a singlet \( B_\mu \) associated with \( U(1)_N \).

There are four neutral bosons: a massless \( \gamma \) and three massive ones: \( Z, Z', Z'' \). The lightest one, say the \( Z \), corresponds to the Weinberg-Salam neutral boson. Assuming the approximation \( u \gg v' \gg v, v'', w \) the extra neutral bosons, say \( Z', Z'' \), have masses which depend mainly on \( u, v' \).

Concerning the charged vector bosons, as in the model of Refs. [3] there are doubly charged vector bosons and there are doublets of \( SU(2) \) \( (X^+_\mu, X^0) \) and \( (\bar{X}^0_\mu, X^-_\mu) \) which pro-
duce interactions like $\bar{\nu}_a L \gamma^\mu l_{aL} X^+_\mu$ and $\bar{\nu}_a L \gamma^\mu \nu_{aL} X^0_\mu$, as in model I of Ref. [2]. We have also the $V^\pm$ vector bosons with interactions like $\bar{\nu}_a L \gamma^\mu l_{aL} V^\mp$.

**B. $n = 4, 5$ models**

Next, we consider $n = 4, 5$ models. Although the $SU(3)_c$ gauge symmetry is the best candidate for the theory of the strong interactions, there is no fundamental reason why the colored gauge group must be $SU(3)_c$. In fact, it is possible to consider other Lie groups. In general we have the possibilities $SU(n)$, $n \geq 3$ [13].

In particular, models in which quarks transform under the fundamental representations of $SU(4)_c$ and $SU(5)_c$ were considered in Refs. [3] and [4] respectively. These models preserve the experimental consistency of the standard model at low energies. For instance, in the $SU(5)_c \otimes SU(m)_L \otimes U(1)_N$ model a Higgs field transforming as the 10 representation of $SU(5)_c$ breaks the symmetry as follows [7]

$$SU(5)_c \otimes SU(m)_L \otimes U(1)_N$$

$$\downarrow \langle 10 \rangle$$

$$SU(3)_c \otimes SU(2)' \otimes SU(m)_L \otimes U(1)_N.$$ (2.5)

Later the electroweak symmetry will be broken and the remaining symmetry will be $SU(3)_c \otimes SU(2)' \otimes U(1)_{em}$ as in the models with $m = 3, 4$ considered above. Notice that, due to the relation between the color degrees of freedom and the number of families, it is necessary to introduce four and five families for $n = 4$ and $n = 5$ respectively.

**III. OTHER POSSIBLE EXTENSIONS**

Other possibilities are, models with left-right symmetry in the electroweak sector $SU(n)_c \otimes SU(m)_L \otimes SU(m)_R \otimes U(1)_N$ and also models with horizontal symmetries $G_H$ i.e., $SU(n)_c \otimes SU(m)_L \otimes U(1)_N \otimes G_H$. 
A. Left-right symmetries

In models with left-right symmetry the $V - A$ structure of weak interactions is related to the mass difference between the left- and right- gauge bosons, $W_L^\pm$ and $W_R^\pm$, respectively, as a result of the spontaneous symmetry breaking [14].

This sort of models is easily implemented in the 3-3-1 context by adding a new lepton $E$. For instance, in models with left-handed leptons transforming as $(\nu_a, l_a^- , E_a^+)^T_L$ the right-handed triplet is $(\nu_a, l_a^- , E_a^+)^T_R$. In the quark sector, the left-handed components are as in Ref. [1] and similarly the right-handed components in such a way that anomalies cancel in each chiral sector. Explicitly, the charge operator is defined as

$$ Q = I_{3L} + I_{3R} + N $$

(3.1)

where $I_{3L(3R)}$ are of the form $(1/2)(\lambda_3 - \sqrt{3}\lambda_8)$. The Higgs multiplet $(\mathbf{3}, \mathbf{3}^*, 0)$ and its conjugate give mass to all fermions but in order to complete the symmetry breaking it is necessary to add more Higgs multiplets. Details will be given elsewhere.

B. Horizontal Symmetries

For example, if $G_H = SU(2)_H$ there are no additional conditions to cancel anomalies since $SU(2)$ is a safe group. For instance, with $n = 3$ the three generations can transform in the adjoint representation of $SU(2)_H$. Another possibility is $G_H = SU(3)_H$ with the three generations in the fundamental representation. In this case it is necessary to introduce right-handed neutrinos. To avoid anomalies, for example in the models of Refs. [1], we can choose either i) all left-handed fermions are in $\mathbf{3}$ and the right-handed ones in $\mathbf{3}^*$, or ii) the left-handed components of the charge $2/3$ and the right-handed components of the charge $-1/3$ transform as a $\mathbf{3}$, while the right-handed components of the charge $2/3$ and the left-handed components of the charge $-1/3$ quarks transform as $\mathbf{3}^*$. Similarly in the leptonic sector [15]. The left-handed (right-handed) components of the exotic quarks transform as $\mathbf{3}$
The consequences of these horizontal symmetries in 3-3-1 models on the mass spectra of quarks and leptons deserve detailed studies.

C. Embedding in $SU(6)$

There are also the grand unified extensions of all the possibilities we have treated above.

For example, it is possible to embed the 3-3-1 models in a simple group as $SU(6)$ [16]. The group $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ has rank 5 and it is a subgroup of $SU(6)$. In the last group, it has been shown that the anomalies, $A$, of 15 and $6^*$ are such that $A(15) = -2A(6^*)$ [17]. Then, pairs of 15 and $15^*$; $6^*$ and 6 [18] and, finally one 15 and two $6^*$ are the smallest anomaly free irreducible representations in $SU(6)$. On the other hand, the representation 20 is safe.

Just as an example, let us consider the $SU(6)$ symmetry which is a possible unified theory for the $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ models of Refs. [1,2]. Using the notation of Ref. [25], in the entry $(a, b)_f(N)$, $a$ is an irreducible representation of $SU(3)_c$ and $b$ is an irreducible representation of $SU(3)_L$. The subindex $f$ means, in an obvious notation, the respective fields of the model and the second parenthesis contains the value of the $U(1)_N$ generator when acting on the states in the $(a, b)$.

Let us consider the 3-3-1 model in which the leptons transform as $(1, 3^*, -1/3)$ under the 3-3-1 factors: $(\nu^c, \nu, l)^T_L$ and quarks as in (2.1) (see Sec.IIA). There are 68 degrees of freedom. Left-handed charged leptons and three of the right-handed $d$-type quarks are in the following representations, three $6^*$:

$$6^*_a = (3^*, 1)_{d^c_{jL}}(+1/3) + (1, 3^*)_{aL}(-1/3), \quad (3.2)$$

where $a = e, \mu, \tau, j = 1, 2, 3$.

Next, two quark generations transforming as $(3, 3, 0)$ and the other two right-handed $d$-type quarks are in two $15$

$$15_{Q_{iL}} = (3^*, 1)_{d^c_{iL}}(+1/3) + (1, 3^*)_{X_{iL}}(-1/3) + (3, 3)_{Q_{iL}}(0), \quad (3.3)$$
where $i = 1, 2$; $X^c_{1L}$ are two antitriplets of new left-handed leptons with charge $(0, 0, -1)$.

The other quark generation is in one 20

$$20_{Q_{3L}} = (1, 1)_{N_{1L}}(0) + (1, 1)_{N_{2L}}(0) + (3, 3^*)_{Q_{3L}}(+1/3) + (3^*, 3)_{Q'_{L}}(-1/3), \quad (3.4)$$

with $N_{iL}$, $i = 1, 2$ neutral leptons and $Q'_{L}$ new quarks trasforming as antitriplets under $SU(3)_c$. One of the charge $2/3$ quarks are in one $6^*$

$$6^*_{t_L} = (3^*, 1)_{t^c_L}(-2/3) + (1, 3^*)_{X^c_{1L}}(+2/3), \quad (3.5)$$

where $X^c_{1L}$ is an antitriplet of extra leptons with $(1, 1, 0)$ electric charges. The other 3 charge $2/3$ quarks are in three $6$

$$6_{u_{jR}} = (3, 1)_{u_{jR}}(+2/3) + (1, 3)_{X'_{jL}}(-2/3), \quad (3.6)$$

where $X'_{jL}$ are three triplets of leptons with charges $(1, 1, 0)$. The quarks $Q'_{L}$ in (3.4) has their right-handed components in three $6^*$

$$6^*_{Q'_{jR}} = (3, 1)_{Q'_{jR}}(+1/3) + (1, 3)_{X_{3R}}(-1/3). \quad (3.7)$$

Finally, there are the singlets of $SU(6)$ corresponding to the usual right-handed charged leptons $l^c_{R}$, new leptons $X_{jL}$, $X'_{aL}$ and $N_{iR}$, where $j = 1, 2, 3, \alpha = 1, 2, 3; 4; i = 1, 2$ and $SU(3)_L \otimes U(1)_N$ indices have been omitted.

Maybe before unification, the model must be embedded in a $(n - m - 1, n > m)$ model. In fact, it is not a trivial issue to show that the unification in $SU(6)$ may actually occur [20].

This is so, because in 3-3-1 the couplings $\alpha_c$ and $\alpha_{3L}$ have $\beta_c > \beta_{3L}$. Notice however that, in order to put all fermion fields of 3-3-1 in $SU(6)$ multiplets, it was necessary to include new fields. It means that these extra fields have to be added to the minimal 3-3-1 model, and their effects in the $\beta$-functions must be taken into account. Therefore, we may have to consider mass threshold corrections for the $\beta$-functions, since the new particles could have masses below the unification energy scale, or even, we may not assume the decoupling theorem. We recall that in the SM with two Higgs doublets the decoupling theorem [21]
must not be necessarily valid, since there are physical effects proportional to $m_{\text{Higgs}}^2$. Hence, it could be interesting to study the way in which the masses of the extra Higgs and exotic quarks in the model become large, as it has been done in the standard model scenario for an extended Higgs sector \cite{22} or for the mass difference between fermions of a multiplet \cite{23}. It means that there is no “grand desert” if 3-3-1 models are realized in nature.

This situation also appears when we consider the embedding of the SM in 3-3-1. The last model has fields which do not exist in the minimal SM, but which are in the same multiplet of 3-3-1 with the known quarks. For instance, the quarks $J$’s have to be added to the SM transforming as $(3, 1, Q_J)$ under the 3-2-1 factors. The scalar and vector boson sectors of the SM have also to be extended with new fields. Hence, we must add scalar fields transforming as (i) four singlets $(1, 1, Y_S)$: one with $Y_S = 0$, one with $Y_S = 1$ and two with $Y_S = 2$, (ii) four doublets $(1, 2, Y_D)$: one with $Y_D = -3$ and three with $Y_D = 1$; finally, (iii) one triplet $(1, 3, -2)$. It is also necessary to add extra vector bosons $(U'^+, V'^+)$ which transform as $(1, 2, 3)$. For this reason we believe that 3-3-1 models are not just an embedding of the SM but an alternative to describe the same interactions.

IV. CONCLUSIONS

The 3-3-1 models are in fact interesting extensions of the standard model. They give partial answers to some questions put forward by the later model and it is also important that new physics could arise at not too high energies, $\sim 1$ TeV \cite{24}. For instance this sort of models predicts new processes in which the initial states have the same electric charge as $f f \rightarrow W^-V^-$. This processes have only recently begun to be studied \cite{25,26}. Also in some extensions of these models with spontaneous and/or explicit breaking of $L + B$ symmetry it is possible to have processes with $|\Delta L| = 2$ on kaon decays $k^+ \rightarrow \pi^-\mu^+\mu^+, \pi^-\mu^+e^+$, and too $|\Delta L| = 2$ decays of $D$ and $B$ mesons. Experimental data imply $B(K^+ \rightarrow \pi^-\mu^+\mu^+) < 1.5 \times 10^{-4}$ \cite{27}. The process $e^-e^- \rightarrow W^-W^-$ which also could occur in some extensions of
the 3-3-1 models has been recently investigated in other context [26].

Another interesting feature of this kind of models is that they include some extensions of the Higgs sector in the standard model: more doublets, single and doubly charged, triplets, etc. The scalar sector of these models deserves detailed study too.

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