

Heavy charged leptons in an $SU(3)_L \otimes U(1)_N$ model

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We consider an $SU(3)_L \otimes U(1)_N$ model for the electroweak interactions which includes extra charged leptons which do not mix with the known leptons. These new leptons couple to Z^0 only through vector currents. We consider constraints on the mass of one of these leptons coming from the Z^0 width and from the muon $(g - 2)$ factor. The last one is less restrictive than the former.

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Recently, it was pointed out that models with $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ symmetry have interesting features and could be possible extensions of the standard model for the interactions of quarks and leptons [1-3].

In order to make the model anomaly-free, two of the three quark generations transform identically and one generation, it does not matter which, transforms in a different representation of $SU(3)_L \otimes U(1)_N$. One can easily check that all gauge anomalies cancel out in this theory. Although each generation is anomalous, this type of construction is only anomaly-free when the number of generations is divisible by 3. Thus three generations are singled out as the simplest nontrivial anomaly-free $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ model.

Here we will consider a model which has the same quark sector of Ref. [1] but with a different leptonic sector. Let us start by defining the charge operator as

$$\frac{Q}{e} = \frac{1}{2} (\lambda_3 - \sqrt{3}\lambda_8) + N, \quad (1)$$

the λ 's being the usual Gell-Mann matrices of $SU(3)$ and N is the $U(1)_N$ charge.

The leptonic sector includes, in addition to the usual charged leptons and their respective neutrinos, charged heavy leptons and transform as triplets $(\mathbf{3}, 0)$ under $SU(3)_L \otimes U(1)_N$:

$$\psi_{aL} = \begin{pmatrix} \nu'_a \\ e'^-_{aL} \\ E'^+_{aL} \end{pmatrix}_L \sim (\mathbf{3}, 0), \quad (2)$$

where $a = 1, 2, 3$ is the family index. The primed fields are symmetry eigenstates. In the $SU(3)_L \otimes U(1)_N$ model considered in Ref. [1] all charged leptons degrees of freedom, i.e., $e^0_L, (e_R)^c$, belong to the same triplet. Hence there are no right-handed singlets. However, in the present model, only left-handed fields appear in Eq. (2) and for this reason we have to add the corresponding right-handed components, $e'^-_{aR} \sim (\mathbf{1}, -1)$ and $E'^+_{aR} \sim (\mathbf{1}, +1)$. The introduction of right-handed neutrinos is optional.

The addition of the right-handed singlets does not change the anomaly cancellation since the new leptons have opposite charge in relation to the known charged leptons.

The model has an extra global $U(1)$ symmetry. Hence we can assign a lepton number for every field in Eq. (2). Assuming that all fields in Eq. (2) have the same lepton number, the mass term $\bar{\psi}^c_{aL} \psi_{bL}$ is forbidden. Thus there is no mixing between the e'^-_{aL} and E'^+_{aL} leptons. Since we have not introduced right-handed neutrinos, they remain massless.

In order to generate lepton masses, we introduce the following Higgs triplets ρ and χ :

$$\begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{++} \end{pmatrix} \sim (\mathbf{3}, 1), \quad \begin{pmatrix} \chi^- \\ \chi^{--} \\ \chi^0 \end{pmatrix} \sim (\mathbf{3}, -1). \quad (3)$$

The third Higgs triplet $\eta \sim (\mathbf{3}, 0)$ which is needed in the quark sector would give mass to the neutrinos if we have introduced right-handed neutrinos transforming as singlets under $SU(3)_L \otimes U(1)_N$. Here we will not consider in detail the gauge sector since it is the same as in Ref. [1]. Let us just remember that there are three charged vector bosons W^+, V^+, U^{++} and two neutral ones Z and Z' .

The Yukawa interaction in the leptonic sector is

$$\mathcal{L}_l = -G_{ab} \bar{\psi}_{aL} e'^-_{bR} \rho - G'_{ab} \bar{\psi}_{aL} E'^+_{bR} \chi + \text{H.c.} \quad (4)$$

In particular the mass term is

$$\mathcal{L}_m = -u G_{ab} e'^-_{aL} e'^-_{bR} - w G'_{ab} E'^+_{aL} E'^+_{bR} + \text{H.c.}, \quad (5)$$

where u (w) is the vacuum expectation value (VEV) of the ρ^0 (χ^0). We can diagonalize the matrices in Eq. (5) defining

$$\begin{aligned} e'^-_{aL} &= U^L_{ab} e^-_{bL}, & e'^-_{aR} &= U^R_{ab} e^-_{bR}, \\ E'^+_{aL} &= V^L_{ab} E^+_{bL}, & E'^+_{aR} &= V^R_{ab} E^+_{bR}; \end{aligned} \quad (6)$$

the unprimed fields are mass eigenstates which will be denoted by e^-, μ^-, τ^- and E^+, M^+, T^+ . Notice that the masses of the new leptons are proportional to the VEV w , which is in control of the $SU(3)$ symmetry and could be very heavy.

Next, let us consider the current-vector boson interactions which are read off from

$$\begin{aligned} \mathcal{L}_F &= \bar{R} i \gamma^\mu (\partial_\mu + i g' B_\mu N_R) R \\ &+ \bar{L} i \gamma^\mu \left(\partial_\mu + \frac{i g'}{2} B_\mu N_L + \frac{i g}{2} \boldsymbol{\lambda} \cdot \mathbf{W}_\mu \right) L, \end{aligned} \quad (7)$$

where R (L) denotes any right-handed singlet (left-handed triplet).

The electric charge is defined as

$$|e| = \frac{g \sin \theta}{(1 + 3 \sin^2 \theta)^{\frac{1}{2}}}, \quad (8)$$

with $t \equiv \tan \theta = g'/g$. In terms of the weak mixing angle θ_W defined as $1/\cos \theta_W = M_Z/M_W$, we can write down

$$t^2 = \frac{\sin^2 \theta_W}{1 - 4 \sin^2 \theta_W}. \quad (9)$$

The charged current interactions in terms of the mass eigenstates are

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_a [\bar{e}_{aL} \gamma^\mu \nu_{aL} W_\mu^- + \bar{E}_{aL} \gamma^\mu K_{ab} \nu_{bL} V_\mu^+ + \bar{e}_{aL} \gamma^\mu K_{ab}^\dagger E_{bL} U_\mu^-] + \text{H.c.}, \quad (10)$$

where we have defined $\nu_{aL} = U_{ab}^\dagger \nu'_{bL}$ and the mixing matrix K is defined as $K = V^{L\dagger} U^L$. The gauge bosons V_μ^+ and U_μ^- have a mass greater than 4 TeV [1].

In this model there is also an additional neutral vector boson Z'^0 with a mass greater than 40 TeV [1]. The neutral currents have the form

$$J_Z^\mu = -\frac{g}{2c_W} [a_L(f) \bar{f} \gamma^\mu (1 - \gamma_5) f + a_R(f) \bar{f} \gamma^\mu (1 + \gamma_5) f] \quad (11)$$

coupled to the Z^0 , and

$$J_{Z'}^\mu = -\frac{g}{2c_W} [a'_L(f) \bar{f} \gamma^\mu (1 - \gamma_5) f + a'_R(f) \bar{f} \gamma^\mu (1 + \gamma_5) f] \quad (12)$$

coupled to the Z'^0 , where f denotes any fermion.

Explicitly one has

$$a_L(\nu'_a) = \frac{1}{2}, \quad a_R(\nu_a) = 0, \quad (13)$$

$$a'_L(\nu'_a) = \frac{1}{2} \left(\frac{1-4x}{3} \right)^{\frac{1}{2}}, \quad a'_R(\nu'_a) = 0,$$

for neutrinos,

$$a_L(e'_a) = -\frac{1}{2} + x, \quad a_R(e'_a) = x, \quad (14)$$

$$a'_L(e'_a) = \frac{1}{2} \left(\frac{1-4x}{3} \right)^{\frac{1}{2}}, \quad a'_R(e'_a) = -x \left(\frac{3}{1-4x} \right)^{\frac{1}{2}},$$

for the lightest charged leptons e_a , and

$$a_L(E'_a) = a_R(E'_a) = -x, \quad (15)$$

$$a'_L(E'_a) = -\left(\frac{1-4x}{3} \right)^{\frac{1}{2}}, \quad a'_R(E'_a) = x \left(\frac{3}{1-4x} \right)^{\frac{1}{2}},$$

for the heavy charged leptons E_a , with $x \equiv \sin^2 \theta_W$.

Notice that the heavy leptons E'_a have pure vector current interactions with the Z^0 neutral gauge boson. From

Eqs. (13)–(15) we see that the Glashow-Iliopoulos-Maiani (GIM) mechanism is implemented.

The charged Higgs boson interaction Lagrangian is

$$\mathcal{L}_{YI} = -\frac{m_a}{u} \bar{\nu}_{aL} e_{aR} \rho^+ - \frac{m_b}{u} K_{ab} \bar{E}_{aL} e_{bR} \rho^{++} - \frac{M_b}{w} K_{ab} \bar{\nu}_{aL} E_{bR} \chi^- - \frac{M_b}{w} K_{ab}^\dagger \bar{e}_{aL} E_{bR} \chi^{--} + \text{H.c.}, \quad (16)$$

where m_a and M_a denote the mass of e_a and E_a leptons respectively. The heavy charged leptons in this model do not belong to any of the four types of heavy leptons usually considered in the literature: (i) sequential leptons, (ii) paraleptons, (iii) ortholeptons, or (iv) long-lived penetrating particles; hence, the experimental limits already existing [4] do not apply directly to them.

For example, a direct search for heavy leptons produced in e^+e^- colliders has been done, but with the heavy leptons being assumed coupled to the Z^0 in the same way as ordinary leptons. These heavy sequential charged and neutral leptons have been excluded except if both masses are larger than 42.8 GeV [5]. In the present model the new charged leptons have couplings to the neutral vector bosons (Z^0, Z'^0) which are different from those of the lightest leptons as can be seen from Eqs. (14) and (15).

The main decay modes of the new leptons are those among the exotic leptons themselves as $M^+ \rightarrow E^+ \nu_e \bar{\nu}_\mu$, assuming $M_M > M_E$.

Search for these charged leptons could be made in colliding-beam experiments $e^+e^- \rightarrow L^+L^-$, pair photoproduction $\gamma + Z \rightarrow L^+L^-Z^*$ and in neutrino experiments $\nu + Z \rightarrow L^- + Z^*$ where L^\pm denotes E^\pm, M^\pm or T^\pm [6].

Decays as $L^+ \rightarrow \bar{\nu}_L + \text{hadrons}$ imply hadrons involving exotic quarks with charge $5/3$ and $-4/3$.

Next, we consider some possible constraints on the new leptons masses. The partial decay width for the Z^0 decaying into massless fermions is [4] $\Gamma(Z \rightarrow \bar{f}f) = [C(G_F M_Z^3)/6\sqrt{2}\pi][V_i^2 + A_i^2]$, where $V^i = a_L^i + a_R^i$ and $A^i = a_L^i - a_R^i$ with a_L^i, a_R^i defined in Eqs. (13)–(15). For leptons, $C = 1$. We see that $V_{e_a} = -1/2 + 2x$, $A_{e_a} = -1/2$ and $V_{E_a} = -2x$, $A_{E_a} = 0$. In the massless limit the contribution of one of the exotic leptons, say E^+ , to the Z^0 partial width is $0.84 \times \Gamma(Z \rightarrow e^+e^-)$. It means that we have to consider corrections for massive fermions. Assuming that $M_E < M_Z/2$ one has [7]

$$\Gamma(Z \rightarrow \bar{E}E) = \frac{G_F M_Z^3}{6\sqrt{2}\pi} (1 - 4\mu_E)^{\frac{1}{2}} (1 + 2\mu_E) V_E^2, \quad (17)$$

since $A_E = 0$ and $\mu_E = M_E^2/M_Z^2$. Assuming that the contribution for the $Z \rightarrow \bar{E}E$ is of the order of 20 MeV, which is compatible with the uncertainty in the measurement of the total Z^0 width [8], we conclude that the mass of the E^+ must be restricted to the interval 38.17–45.57 GeV. The other two exotic leptons may have masses larger than $M_Z/2$.

On the other hand, there are contributions to muon $g-2$ via transitions such as $\mu^- \rightarrow M^+ U^{--} \rightarrow \mu^-$. As this quantity has been measured very accurately [9], it can be used to restrict the range of the parameters in a

given model for the electroweak interactions [10]. General expressions valid for an arbitrary gauge model have been given in Ref. [11], from which it is easy to verify that the contribution of a lepton- E_a to $a_\mu = (g-2)_\mu/2$ is

$$a_\mu^U = a_\mu^W \left(\frac{M_a}{m_\mu} \right) \left(\frac{M_W^2}{M_U^2} \right) \sim a_\mu^W \left(\frac{M_a}{m_\mu} \right) \times 10^{-4}, \quad (18)$$

if $m_\mu \ll M_a \ll M_U$, where a_μ^W is the usual one-loop weak contributions and M_U is the U_μ^{--} vector boson mass. Hence, these contributions are negligible even when $M_a \sim M_Z/2$.

There are also contributions to the muon $g-2$ due to charged scalars such as $\mu^- \rightarrow \chi^- \nu, \rho^- \nu \rightarrow \mu^-$ and $\mu^- \rightarrow \chi^{--} M^+, \rho^{--} M^+ \rightarrow \mu^-$. In this case a factor $(M_a/m_\mu)(M_W^2/m_\phi^2)$ appears, where ϕ is any charged

scalar. These contributions are also negligible if $m_\phi \gg M_W$, as is the case, since the charged scalars have masses proportional to $w \simeq 8$ TeV which is the VEV that induces the first symmetry breaking [1].

Anyway, the scalar contributions could be negligible because the $\mu-\phi$ coupling is small. There could be also a cancellation between both contributions from charged vector and scalar bosons [12]. Hence the muon $g-2$ is not so restrictive on the heavy lepton and charged scalar masses. The contributions to electron $g-2$ are smaller than those to the muon for factors m_e/m_μ or m_e^2/m_μ^2 .

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