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# Anomaly-free left-right-symmetric models with gauged baryon and lepton numbers

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A left-right-symmetric extension of the standard electroweak interaction model is presented in which baryon- ($B$-) and lepton- ($\mathcal{L}$-) number conservation are considered as spontaneously broken gauge symmetries. The gauge, global, and the mixed gauge-gravitational anomalies in the model are canceled by invoking new fermion matter that carries baryon as well as lepton numbers. We find a class of models in which the exotic fermions carry the same electric charges as the $N$ families of conventional fermions but different $B$ and $\mathcal{L}$ charges. The Higgs structure in this case allows a light massive neutral boson with a lower bound of 120 GeV.

In nature, all indications are that elementary-particle interactions conserve baryon ($B$) and lepton ($\mathcal{L}$) numbers. This observation may be taken as indicative of the fact that the $SU(2)_L \times U(1)_Y$ gauge symmetry of the standard model of electroweak interactions[1] is only an effective residual gauge symmetry that has been successfully probed at the presently attained low energies. It is conceivable that $B$ and $\mathcal{L}$ numbers are the charges of gauge theories. Such a possibility has been discussed in Ref. 2 and later in Ref. 3. In the latter case the gauged $U(1)_B$ and $U(1)_{\mathcal{L}}$ are simply added to the standard model and do not play any role in the definition of electric charge. We follow the idea of Ref. 2 in which $B$ and $\mathcal{L}$ play an important role in the definition of electric charge. In order to incorporate baryon- and lepton-number conservation as gauge symmetries the quarks are assigned a baryon number of $\frac{1}{3}$ units and the leptons are assigned one unit of lepton number. The lepton number in the present context is defined as the sum of the individual lepton number of each generation of leptons: i.e.,

$$\mathcal{L}=\mathcal{L}^{(e)}+\mathcal{L}^{(\mu)}+\mathcal{L}^{(\tau)} , \tag{1}$$

with conventional weak interactions described by $SU(2)_L$-gauge symmetry for the left-handed doublet, the full symmetry of the elementary-particle interactions is[2] $SU(2)_L \times U(1)_R \times U(1)_B \times U(1)_{\mathcal{L}}$ where $U(1)_R$ couples to the right-handed fermions only. Note that if we do not take the lepton number as the diagonal sum of the lepton numbers of the individual species of leptons as in Eq. (1), then the full symmetry of electroweak interactions is $SU(2)_L \times U(1)_R \times U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the observed lepton number that appears in Eq. (1) is the spontaneously broken low-energy manifestation of the lepton-number gauge symmetry $U(1)_e \times U(1)_\mu \times U(1)_\tau$. In this paper we will consider only the simple case of treating the lepton number as in Eq. (1) and treat the general case in a future publication. The emergence of $U(1)_R$ that couples only to right-handed fermions is very suggestive of the fact that nature may be symmetric between left and right[4] and the gauge structure $SU(2)_L \times U(1)_R \times U(1)_B \times U(1)_{\mathcal{L}}$ may have descended from the left-right-symmetric gauge symmetry of electroweak interactions which we take to be

$$G = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)_{\mathcal{L}} \tag{2}$$

with gauge couplings $g_C$, $g_L$, $g_R$, $g_B$, and $g_{\mathcal{L}}$ and $SU(3)_C$ is the color group which describes the strong interaction of quarks. Under $G$, the left ($R_L$) and the right ($R_R$) representation of the conventional quarks and leptons are taken to transform as

$$\begin{aligned}
\text{Quarks:}\quad q_{iL} &= \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L = (3,2,1,\tfrac{1}{3},0) , \\
q_{iR} &= \begin{pmatrix} u_i \\ d_i \end{pmatrix}_R = (3,1,2,\tfrac{1}{3},0) , \\
\text{Leptons:}\quad L_{iL} &= \begin{pmatrix} e_i \\ \nu_i \end{pmatrix}_L = (1,2,1,0,1) , \\
L_{iR} &= \begin{pmatrix} e_i \\ \nu_i \end{pmatrix}_R = (1,1,2,0,1) ,
\end{aligned} \tag{3}$$

where $i$ is the family index.

The electric charge operator which is the generator of the unbroken $U(1)_{em}$ group in this theory is

$$Q_{em} = T_L + T_R + \tfrac{1}{2}T_B - \tfrac{1}{2}T_{\mathcal{L}} , \tag{4}$$

where $T_{L,R,B,\mathcal{L}}$ are the diagonal generators of $SU(2)_L$, $SU(2)_R$, $U(1)_B$, and $U(1)_{\mathcal{L}}$, respectively.

In order to entertain the possibility of the observed violation of parity due to spontaneous symmetry breaking, we impose the discrete symmetry left$\leftrightarrow$right. This reduces the gauge couplings to three since $g_L = g_R$ at the scale where left-right symmetry is restored.

In this extension of the standard model, the gauge anomalies[5] of the quarks and leptons no longer cancel. This is also the point of departure from the conventional left-right-symmetric model in which, as in the standard model, the anomalies of the quarks cancel the anomalies of the leptons.[6] Electroweak and strong interactions based on $G$ in Eq. (2) predict new fermionic matter for the consistency of the theory.

In order to see which anomalies survive, let the gauge fields of $G$ be denoted by $G^\alpha$ ($\alpha=1,\ldots,8$), $W_L^i$, $W_R^i$ ($i=+,-,0$), $B$, and $L$. Also let the anomaly coefficients with three gauge fields at the vertices of the anomaly triangle be denoted by $A(G^3), A(W^2G),\ldots$. Since the fermion currents coupling to $G,B,L$ are vectorlike and the fact that SU(2) is by nature anomaly-free the only surviving anomaly coefficients are $A(BW_L^2)$, $A(BW_R^2)$, $A(LW_L^2)$, and $A(LW_R^2)$. For one family of conventional quarks and leptons the values of these coefficients are

$$A(BW_L^2)=\tfrac{1}{2},\quad A(BW_R^2)=-\tfrac{1}{2}\,,$$
$$A(LW_L^2)=\tfrac{1}{2},\quad A(LW_R^2)=-\tfrac{1}{2}\,. \tag{5}$$

For the theory to be renormalizable, all anomalies must be separately canceled. This can be arranged by introducing exotic quarks and leptons. Let the representation of one of the exotic family of fermions be

$$F_i=(m_{Ci},m_{Li},m_{Ri},\alpha_i,\beta_i)_L+(m_{Ci},m_{Ri},m_{Li},\alpha_i,\beta_i)_R\,, \tag{6}$$

where $i$ is the family index of the exotic fermion, $m$'s are the dimensions of the group representations, and $\alpha$ and $\beta$ are the baryon and lepton numbers, respectively. We have chosen the representation such that the theory is manifestly left-right symmetric. The constraints to be satisfied by these exotic representations that cancel the anomalies of $N$ families of conventional quarks and leptons are

$$m_{Ci}\alpha_i[m_{Ri}T_2(m_{Li})-m_{Li}T_2(m_{Ri})]+\frac{N}{2}=0\,,$$
$$m_{Ci}\beta_i[m_{Ri}T_2(m_{Li})-m_{Li}T_2(m_{Ri})]+\frac{N}{2}=0\,. \tag{7}$$

Here summation over $i$ is implicit and $T_2(m)$ denotes the second Dynkin index[7] of the $SU(2)_{L,R}$ representation and is equal to

$$T_2(m)=\tfrac{1}{12}(m-1)m(m+1)\,. \tag{8}$$

There are many choices of exotic fermions which satisfy Eq. (7). The simplest solutions are the exotic-fermion family transforms under the gauge group as (a) $(1,2,1,-N,-N)_L+(1,1,2,-N,-N)_R$, or (b) $(3,2,1,-N/3,-N/3)_L+(3,1,2,-N/3,-N/3)_R$. These solutions do not have equal numbers of representations transforming as a singlet and triplet under $SU(3)_C$ as for conventional fermion families. In the following we will consider some solutions which contain equal numbers of $SU(3)_C$ singlets and triplets.

*Mirror fermions.* Under $G$, mirror fermions transform in exactly the same way as conventional quarks and leptons but carry opposite chiralities:

$$(3,2,1,\tfrac{1}{3},0)_R+(3,1,2,\tfrac{1}{3},0)_L+(1,2,1,0,1)_R+(1,1,2,0,1)_L\,. \tag{9}$$

This solution of anomaly cancellation is by no means trivial since mirror fermions occur naturally in schemes of grand unification with at least three families of conventional quarks and leptons.[8] In the model under consideration, three mirror fermion families are required to cancel the anomalies of three families of conventional quarks and leptons.

*Fermions in SU(2) representation with dimensionality m.* Here we consider the case in which fermions transform under $SU(2)_{L,R}$ as $m$ and under $SU(3)_C$ as 3 and 1 which carry baryon numbers only or lepton numbers only, respectively. We also demand that just one such family is required to satisfy Eq. (7). This family is

$$(3,m,1,\alpha,0)_L+(3,1,m,\alpha,0)_R+(1,m,1,0,\beta)_L+(1,1,m,0,\beta)_R\,. \tag{10}$$

From Eq. (7), we obtain

$$3\alpha\tfrac{1}{6}(m-1)m(m+1)=-N\,,$$
$$\beta\tfrac{1}{6}(m-1)m(m+1)=-N\,. \tag{11}$$

From these equations, we immediately see that $3\alpha+\beta=0$ and the baryon and lepton numbers have opposite signs to the conventional quarks and leptons. If $\alpha=-\frac{1}{3}$ and $\beta=-1$, we have

$$m=2,N=1;\quad m=3,N=4;\quad m=4,N=10;\ldots\,. \tag{12}$$

Thus the family number is constrained.

*Quarklike and leptonlike fermions.*[9] We now consider a very interesting case in which there are fermions which transform under $SU(3)_C\times SU(2)_L\times SU(2)_R$ exactly like the conventional quarks and leptons. We call them the quarklike fermion $F_Q$ and leptonlike fermion $F_{\mathcal{L}}$ (one family of leptoquark fermion), respectively. They differ from the conventional quarks and leptons in their different $B$ and $\mathcal{L}$ assignments:

$$F_Q=\begin{bmatrix}U\\D\end{bmatrix}:\ (3,2,1,a,b)_L+(3,1,2,a,b)_R\,,$$
$$F_{\mathcal{L}}=\begin{bmatrix}N\\E\end{bmatrix}:\ (1,2,1,x,y)_L+(1,1,2,x,y)_R\,. \tag{13}$$

Using the definition of $Q$ in Eq. (4), we have

$$a-b=2Q_U-1,\quad x-y=2Q_N-1\,,$$
$$Q_U=Q_D+1,\quad Q_N=Q_E+1\,. \tag{14}$$

For one family of leptoquark fermion to cancel the anomalies of $N$ families of conventional quarks and leptons, the baryon and lepton numbers of the leptoquark fermions must satisfy the equations

$$3a+x+N=0,\quad 3b+y+N=0\,. \tag{15}$$

The equations imply $3Q_U+Q_N=2$ which is independent of the number of families of conventional quarks and leptons and also independent of $B$ and $\mathcal{L}$ numbers assigned to leptoquark fermions. Using Eqs. (14) and (15), we can write the $B$ and $\mathcal{L}$ numbers of the leptoquark fermions as

$$\begin{aligned} F_Q &= (3,2,1,a,a-2Q_U+1)_L^{(Q_U,Q_{U-1})} \\ &\quad +(3,1,2,a,a-2Q_U+1)_R^{(Q_U,Q_{U-1})} , \\ F_{\mathcal{L}} &= (1,2,1,-3a-N,-3a-N+6Q_U-3)_L^{(Q_N,Q_{N-1})} \\ &\quad +(1,1,2,-3a-N,-3a-N+6Q_U-3)_R^{(Q_N,Q_{N-1})} , \end{aligned} \tag{16}$$

where the superscripts indicate the electric charges of $U,D,N,E$. It is interesting to notice that it is possible to have the leptoquark fermions carrying the same electric charges as the conventional quarks and leptons ($Q_U=\frac{2}{3}$, $Q_D=-\frac{1}{3}$, $Q_N=0$, $Q_E=-1$). Further we can have the quarklike fermions in the leptoquark fermion family transform exactly as the conventional quarks; this implies

$$a=\tfrac{1}{3},\quad b=0,\quad x=-N-1,\quad y=-N . \tag{17}$$

The family number is related to the baryon and lepton numbers of leptonlike fermions. Alternatively, we can demand the leptonlike fermions to transform exactly as the conventional leptons. In this case, we have

$$a=-\frac{N}{3},\quad b=-\frac{N}{3}-\frac{1}{3},\quad x=0,\quad y=1 . \tag{18}$$

These leptoquark fermions are, after all, not very exotic. At low energy, they would look just like the conventional quarks and lepton. Their difference lies in the gauge interactions at high energies when $G$ is embedded in a grand unifying symmetry.

In the models considered above, there are even numbers of SU(2)-doublet Weyl fermion representations and therefore by Witten's theorem are free from the SU(2) global anomaly.[10] Note also that, due to the left-right-symmetric particle content,

$$\begin{aligned} &\sum_i B(R_{Li})-\sum_i B(R_{Ri})=0 , \\ &\sum_i \mathcal{L}(R_{Li})-\sum_i \mathcal{L}(R_{Ri})=0 , \end{aligned} \tag{19}$$

where $B(R_i)$ and $\mathcal{L}(R_i)$ are the baryon and lepton numbers of the representation $R_i$ and the sum is over all representations of the fermions. Thus the above models are also free from the mixed gauge-gravitational anomalies.[11]

The gauge bosons and the fermions of the theory acquire masses through spontaneous symmetry breaking. The relevant Higgs-scalar representations are a neutral singlet $S$, two SU(2) doublets $\phi_L,\phi_R$ and a bidoublet $\phi_{LR}=\phi$. Their transformation properties under $G$ are

$$\begin{aligned} &S:\ (1,1,1,1,1),\quad \phi:\ (1,2,\bar{2},0,0) , \\ &\phi_L:\ (1,2,1,-\tfrac{1}{2},\tfrac{1}{2}),\quad \phi_R:\ (1,1,2,-\tfrac{1}{2},\tfrac{1}{2}) . \end{aligned} \tag{20}$$

The vacuum expectation values (VEV's) of the Higgs fields, consistent with the extremum of the potential, are

$$\begin{aligned} &\langle S\rangle=\xi,\quad \langle\phi\rangle=\begin{bmatrix}\kappa_1 & 0\\ 0 & \kappa_2\end{bmatrix} , \\ &\langle\phi_L\rangle=\begin{bmatrix}0\\ \eta_L\end{bmatrix},\quad \langle\phi_R\rangle=\begin{bmatrix}0\\ \eta_R\end{bmatrix} . \end{aligned} \tag{21}$$

The vacuum expectation value of $\phi$ not only gives masses to the conventional quarks and leptons but also to the leptoquark matters. In this sense the choice of the Higgs scalars is the most economical. Depending on the relative hierarchy in the magnitude of the various VEV's, the following modes of symmetry breaking are possible:

$$\begin{aligned} &\text{(a)}\quad G\xrightarrow{\xi}\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R\times\mathrm{U}(1)_{B-\mathcal{L}} \\ &\qquad\xrightarrow{\eta_R}\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y\xrightarrow{\eta_L,\langle\phi\rangle}\mathrm{U}(1)_{\mathrm{em}} ; \\ &\text{(b)}\quad G\xrightarrow{\eta_R}\mathrm{SU}(2)_L\times\mathrm{U}(1)'\times\mathrm{U}(1)'' \\ &\qquad\xrightarrow{\xi}\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y\xrightarrow{\eta_L,\langle\phi\rangle}\mathrm{U}(1)_{\mathrm{em}} . \end{aligned} \tag{22}$$

The first mode of descent of $G$ proceeds via usual left-right symmetry with the baryon-lepton number as its Abelian generator.[12] Phenomenological constraints on $\eta_R$ from muon decay, the $K$-long and $K$-short mass difference,[13] imply that the $W_R$ mass and one neutral-gauge-boson mass are in the $>1$-TeV range. Thus in the mode of descent characterized by (a), $W_R$ and two neutral bosons are in the $>1$-TeV range.

The second mode of descent characterized by (b) is the more interesting one from the phenomenological point of view. Although $\eta_R \gg \kappa_1,\kappa_2,\xi,\eta_L$, there exists the possibility of a second neutral boson $Z_2$ that has a lower bound of 120 GeV (Ref. 14). The second neutral boson couples to conventional fermions that are vectorlike and mixes with the neutral boson $Z^0$ of the standard $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$ model. The new interactions do not affect the atomic parity-violation measurements and measurements of the forward-backward asymmetry in the reactions $e^+e^-\to\mu^+\mu^-$ and $e^+e^-\to\tau^+\tau^-$. Planned measurements of the fractional shifts in the mass and width of the standard boson at SLAC and CERN LEP to an accuracy of 1% or less will place further stringent constraints on the mass and coupling of the $Z_2$ boson.

With the above Higgs-boson representations, the leptoquark fermions do not mix with the conventional quarks and leptons if $a\neq\frac{1}{3}$, or $a\neq -N/3$ in Eq. (16). Weak interactions conserve the flavor of the leptoquark fermions. For the solution of Eq. (17), the quarklike fermion $F_Q$ mixes with conventional quarks and, for solution of Eq. (18), the leptonlike fermion $F_{\mathcal{L}}$ mixes with conventional leptons. At present the lower bound on the masses of leptoquark fermions is 26 GeV from KEK TRISTAN (Ref. 15) in search for exotic $e^+e^-\to U\bar{U},D\bar{D},E\bar{E}$.

In the models presented above, although $B$ and $\mathcal{L}$ are spontaneously broken, there is no $B$- or $\mathcal{L}$-violating processes perturbatively in these models. This is because the Higgs bosons with different $B$ and $\mathcal{L}$ numbers do not mix even after spontaneous symmetry breaking and also the gauge interactions do not violate the $B$ or $\mathcal{L}$ number.

Therefore no baryon asymmetry will be generated by exchanging gauge and Higgs bosons. However, significant baryon asymmetry may still be generated by nonperturbative effects due to tunneling between vacua with different baryon numbers.[16]

In conclusion, we have presented a left-right-symmetric electroweak model in which baryon and lepton numbers are treated as spontaneously broken gauge symmetries. A variety of representations that cancel the anomalies of $N$ families of conventional fermions are presented. Our favorites for anomaly cancellation solutions are leptoquark representations. Such solutions are not possible in the model discussed in Ref. 2. The Higgs structure in this case is the most economical one consisting of a singlet, two doublets, and a bidoublet. In this model there exists the possibility of a light massive neutral boson with a lower bound of 120 GeV.

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