Electroweak interactions with gauged baryon and lepton numbers

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The possibility that gauge symmetries associated with baryon and lepton numbers are spontaneously broken symmetries of nature is entertained. In this endeavor, the gauge group of electroweak interactions is $SU(2)\times U(1)^3$. Consistent with neutral-current phenomenology, the spectrum of massive neutral gauge bosons consist of the Z^0 of the standard electroweak model and two additional neutral bosons with mass lower bounds of 120 and 210 GeV which makes these particles prospective candidates for production in the energy regimes of the CERN LEP, Fermilab Tevatron, and the Superconducting Super Collider.

Empirical evidence suggests that baryon and lepton numbers are conserved in strong, weak, and electromagnetic interactions. In the present context, the lepton number (L) is taken to be the sum of the individual lepton numbers L^e, L^μ, L^τ associated with the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. In analogy with electric charge conservation, it is tempting to identify the conserved currents associated with baryon and lepton numbers as coupled to photonlike gauge particles. However, the symmetries associated with baryon[1] and lepton numbers must be broken since no photonlike gauge particles have been observed. With Abelian symmetries assigned to baryon- and lepton-number conservation the gauge symmetry of electroweak interactions is extended from[2] $SU(2)_L \times U(1)_Y$ to[3] $SU(2)_L\times U(1)_R\times U(1)_{\text{baryon}}\times U(1)_{\text{lepton}}$ where $U(1)_R$ couples only to right-handed conventional quarks and leptons. The full symmetry of elementary-particle interactions is taken to be

$$G=SU(3)_C\times SU(2)_L\times U(1)_R\times U(1)_{\text{baryon}}\times U(1)_{\text{lepton}} .$$

Under G the conventional quarks and leptons of the three generations have the transformations

$$\begin{aligned}
&\begin{bmatrix} u_i \\ d_i \end{bmatrix}_L, \begin{bmatrix} c_i \\ s_i \end{bmatrix}_L, \begin{bmatrix} t_i \\ b_i \end{bmatrix}_L \sim (3,2,0,\tfrac{1}{3},0) ,\\
&u_{iR}, c_{iR}, t_{iR} \sim (3,1,1,\tfrac{1}{3},0) ,\\
&d_{iR}, s_{iR}, b_{iR} \sim (3,1,-1,\tfrac{1}{3},0) ;
\end{aligned} \tag{1}$$

$$\begin{aligned}
&\begin{bmatrix} \nu_e^0 \\ e^- \end{bmatrix}_L, \begin{bmatrix} \nu_\mu^0 \\ \mu^- \end{bmatrix}_L, \begin{bmatrix} \nu_\tau^0 \\ \tau^- \end{bmatrix}_L \sim (1,2,0,0,1) ,\\
&e_R^-, \mu_R^-, \tau_R^- \sim (1,1,-1,0,1) ,\\
&\nu_{eR}^0 \nu_{\mu R}^0 \nu_{\tau R}^0 \sim (1,1,1,0,1) ,
\end{aligned} \tag{2}$$

where i denotes the color degrees of freedom. Electric charges in units of the proton charge e of the particle multiplets are assigned through the charge operator Q_{em} which is expressed in terms of the totally commuting generators of the groups $SU(2)_L$, $U(1)_R$, $U(1)_{\text{baryon}}$, $U(1)_{\text{lepton}}$,

$$Q_{\text{em}} = T_L^0 + \tfrac{1}{2}(T_R^0 + T_{\text{baryon}}^0 - T_{\text{lepton}}^0) \tag{3}$$

For future reference, the gauge fields and the gauge couplings associated with the symmetries SU(3), SU(2), $U(1)_R$, $U(1)_{\text{baryon}}$, $U(1)_{\text{lepton}}$ are denoted as G^m ($m=1,\ldots,8$), $W^n=(W_L^+, W_L^-, W_L^0)$, W_R^0, B^0, L^0 and g_c, g_L, g_R, g_B, g_l.

Since the quarks and leptons couple to distinct U(1) gauge symmetries, the triangle anomalies no longer cancel. The anomalies are canceled by introducing mirror fermions. Under G, mirror fermions transform in the same way as the conventional quark and lepton representations but carry opposite chiralities. In the presence of mirror fermions the theory is vectorlike and hence free from anomalies. The choice of mirror fermions for canceling the anomalies is dictated by two observations. The first one has to do with economy in the number of Higgs scalars. The same Higgs representations that break G to $U(1)_{\text{em}}$ are sufficient to give masses not only to the conventional quarks and leptons but also to the mirror fermions. The second observation is that if G descends from a grand unifying symmetry[4] such as $SO(4N+2)$ ($N>2$), it will most inevitably be accompanied by mirror fermions.

The set of Higgs scalars necessary to break G to $U(1)_{\text{em}}$ and give masses to the conventional and mirror fermions consist of two singlets and a doublet with the following transformation properties under $SU(2)_L \times U(1)_R\times U(1)_{\text{baryon}}\times U(1)_{\text{lepton}}$:

$$\begin{aligned}
&A\sim(1,0,1,1),\quad B\sim(1,2,-1,1),\\
&C\sim(2,-1,0,0) .
\end{aligned} \tag{4}$$

The Lagrangian of the model is

$$L=\sum_{m,n}\left(-\tfrac{1}{4}G^{(m)}_{\mu\nu}G^{(m)\mu\nu}-\tfrac{1}{4}W^{(n)}_{\mu\nu}W^{(n)\mu\nu}\right)-\tfrac{1}{4}B^{0}_{\mu\nu}B^{0\mu\nu}-\tfrac{1}{4}L^{0}_{\mu\nu}L^{0\mu\nu}$$
$$+\sum_{f,F}(\bar f_L i\gamma^\lambda D_\lambda f_L+\bar f_R i\gamma^\lambda D_\lambda f_R+\bar F_R i\gamma^\lambda D_\lambda F_R+\bar F_L i\gamma^\lambda D_\lambda F_L)$$
$$+D_\lambda A D^\lambda A^*+D_\lambda B D^\lambda B^*+D_\lambda C^\dagger D^\lambda C+L_{\text{Yukawa}}+V(A,B,C)\;, \tag{5}$$

where f_L, f_R correspond to the conventional left-handed fermion doublets and right-handed singlets, the F's denote the corresponding right-handed mirror-fermion doublets and left-handed mirror-fermion singlets, and the D's denote the appropriate covariant derivatives. The ground state of the system is determined by the vacuum expectation values

$$\langle A\rangle=\alpha,\quad \langle B\rangle=\beta,\quad \langle C\rangle=\begin{bmatrix}\sigma\\0\end{bmatrix} \tag{6}$$

which are solutions to the equations $\partial V/\partial A=\partial V/\partial B=\partial V/\partial C=0$. The potential $V(A,B,C)$ is given by

$$V(A,B,C)=-\mu_A^2AA^*-\mu_B^2BB^*-\mu_C^2CC^\dagger+\lambda_A(AA^*)^2+\lambda_B(BB^*)^2+\lambda_C(CC^\dagger)^2+\lambda_{AB}(AA^*)(BB^*)$$
$$+\lambda_{AC}(AA^*)(CC^\dagger)+\lambda_{BC}(BB^*)(CC^\dagger)+\lambda'(AB)(AB)^*+\lambda''(A^*B)(AB^*)\;. \tag{7}$$

The descent of G to $U(1)_{em}$ depends on the hierarchies in the scales α,β,σ. Two cases of interest are

$$G\xrightarrow{\beta}SU(2)_L\times U(1)'\times U(1)''\xrightarrow{\alpha}SU(2)_L\times U(1)_Y\xrightarrow{\sigma}U(1)_{em}\;, \tag{8}$$

$$G\xrightarrow{\alpha}SU(2)_L\times U(1)_R\times U(1)\xrightarrow{\beta}SU(2)_L\times U(1)_Y\xrightarrow{\sigma}U(1)_{em}\;. \tag{9}$$

After spontaneous symmetry breaking, the spectrum of gauge bosons consists of the charged bosons W_L^+, W_L^- of weak interactions, each with mass $g_L\sigma/\sqrt{2}$, the massless photon A:

$$\frac{A}{e}=\frac{W_L^0}{g_L}+\frac{W_R^0}{g_R}+\frac{B^0}{g_B}-\frac{L^0}{g_l} \tag{10}$$

with electric charge e given by the relation $e^{-2}=g_L^{-2}+g_R^{-2}+g_B^{-2}+g_l^{-2}$ and three massive neutral gauge bosons Z_1, Z_2, Z_3. Out of these, Z_1 is constrained to be almost the Z^0 gauge boson of the standard $SU(2)_L\times U(1)_Y$ model with mass $(91.5\pm1.2\pm1.7)$ GeV and $(93.0\pm1.4\pm3.0)$ GeV as determined by the UA1 and UA2 Collaborations.[5] Constraints on the masses of Z_2 and Z_3 come from parity-violating neutral-current interactions involving the neutrinos and the electrons. The interaction Lagrangian for the various processes is parametrized[6] in terms of the effective couplings:

$$\sqrt{2}G_F^{-1}L=\sum_{q=u,d}\{\bar\nu_\mu\gamma^\xi(1-\gamma_5)\nu_\mu[G_L^q\bar q\gamma_\xi(1-\gamma_5)q+G_R^q\bar q\gamma_\xi(1+\gamma_5)q+\bar e\gamma_\xi(G_V^e-G_A^e\gamma_5)e$$
$$+\delta_{\mu e}\bar e\gamma_\xi(1-\gamma_5)e]+C_{1q}\bar e\gamma^\xi\gamma_5e\bar q\gamma_\xi q+C_{2q}\bar e\gamma^\xi e\bar q\gamma_5\gamma_\xi q\}\;. \tag{11}$$

The experimentally measured values of the various couplings[7] are presented in Table I. Also presented in Table I are the predictions of the model for the various couplings at the value of the weak mixing angle $\sin^2\theta_w=0.22$. For the predictions of the model to fall within two standard deviations of the experimentally measured values of the couplings, the lower bounds on the masses of Z_2 and Z_3 gauge bosons are 120 and 210 GeV. Interestingly enough, these particles fall within the energy regimes of CERN, LEP, Fermilab Tevatron, and the Superconducting Super Collider (SSC). In fitting the neutral-current data the gauge couplings g_B and g_l are taken to be of the same order of magnitude. The massive neutral eigenstates are

$$Z_1=Z^0+\delta I^0,\quad M_{Z_1}\approx M_{Z^0};\quad Z_2=\frac{g_BB^0+g_lL^0}{(g_B^2+g_l^2)^{1/2}},\quad M_{Z_2}\ge 120\text{ GeV};\quad Z_3=I^0-\delta Z^0,\quad M_{Z_3}\ge 210\text{ GeV}\;; \tag{12}$$

where Z^0 is the gauge field of the standard $SU(2)_L\times U(1)_Y$ model,

$$I^0=e(\cos\theta_w)^{-1}(g_B^2+g_l^2)^{-1/2}W_R^0-e(\cos\theta_w)^{-1}g_R^{-1}(g_B^2+g_l^2)^{1/2}(g_B^{-1}B^0-g_l^{-1}L^0),$$

and δ is of order σ^2/β^2 (≤ 0.1). In the second case [Eq. (9)] the U(1) corresponds to the $(B-L)$ gauge symmetry[8] and the lower bounds on the Z_2 and Z_3 masses are 210 GeV.

The fermions derive masses and mixing angles from Yukawa couplings involving only the scalar doublet C. The Yukawa interaction Lagrangian is

$$
\begin{aligned}
L_{\text{Yukawa}} = \sum_{u,d,e,\nu} [& (y_{f^u f^{u'}} \bar{f}^u_L C F^{u'}_R + y_{F^u F^{u'}} \bar{F}^u_R C F^{u'}_L + m_{f^u F^{u'}} \bar{f}^u_L F^{u'}_R + m_{F^u f^{u'}} \bar{F}^u_L f^{u'}_R) \\
& + (y_{f^d f^{d'}} \bar{f}^d_L \tilde{C} F^{d'}_R + y_{F^d F^{d'}} \bar{F}^d_R \tilde{C} F^{d'}_L + m_{f^d F^{d'}} \bar{f}^d_L F^{d'}_R + m_{F^d f^d} \bar{F}^d_L f^{d'}_R) \\
& + (y_{f^\nu f^\nu} \bar{f}^\nu_L C F^{\nu'}_R + y_{F^\nu F^\nu} \bar{F}^\nu_R C F^{\nu'}_L + m_{f^\nu F^\nu} \bar{f}^\nu_L F^{\nu'}_R + m_{F^\nu f^\nu} \bar{F}^\nu_L f^{\nu'}_R) \\
& + (y_{f^e f^{e'}} \bar{f}^e_L \tilde{C} F^{e'}_R + y_{F^e F^{e'}} \bar{F}^e_R \tilde{C} F^{e'}_L + m_{f^e F^{e'}} \bar{f}^e_L F^{e'}_R + m_{F^e f^{e'}} \bar{F}^e_L f^{e'}_R)] + \text{H.c.} \ ,
\end{aligned} \tag{13}
$$

where $\tilde{C} = i\sigma_2 C^*$. After spontaneous symmetry breaking, the generic form of the mass matrices in the fermion-mirror fermion bases (f,F) is

$$
M^u = \begin{bmatrix} y_{f^u f^{u'}} \sigma & m_{f^u F^{u'}} \\ m_{F^u f^{u'}} & y_{F^u F^{u'}} \sigma \end{bmatrix} \tag{14}
$$

where $f^u = u, c, t$ and $F^u = \mathbf{U}, \mathbf{C}, \mathbf{T}$ correspond to the mirror partners of the fermions in f^u. There are similar mass matrices M^d, M^μ, M^e for the fermions $f^d = d, s, b$; $f^e = e, \mu, \tau$; $f^\nu = \nu_e, \nu_\mu, \nu_\tau$ and their mirror counterparts F^d, F^ν, F^e. At present the lower bound on the masses of the mirror fermions comes from the reaction $e^+e^- \to F\bar{F}$ at KEK TRISTAN (Ref. 9). All fermion mass matrices are of dimensionality (6×6). In order to keep the parameters to a minimum when diagonalizing these mass matrices, the bare mass terms between f and F are eliminated by imposing the discrete symmetry $F_L \to -F_L$ and $F_R \to -F_R$. In this case the mass matrices are diagonalized by the (3×3) biunitary transformations $k^u_L, k^u_R, K^u_L, K^u_R$:

$$
M^u_{\text{diag}} = \begin{bmatrix} k^u_L y_{f^u f^{u'}} k^{u\dagger}_R \sigma & 0 \\ 0 & K^u_L y_{F^u F^{u'}} K^{u\dagger}_R \sigma \end{bmatrix} . \tag{15}
$$

The Kobayashi-Maskawa-type mixing matrices are given by the usual formulas $V_{\text{KM}} = k^u_L k^{d\dagger}_L$ and $V^{\text{mirror}}_{\text{KM}} = K^u_L K^{d\dagger}_L$ and each matrix consists of three angles and one phase. Hence the source of CP violation in this model is intrinsic just as in the standard model.

After spontaneous symmetry breaking, there are three leftover physical Higgs scalars. In spite of mixings between the states, there are no tree-level flavor-changing neutral currents[10] due to Higgs-boson exchange in the model. This follows from the fact that the same transformations that diagonalize the fermion mass matrices also diagonalize the Yukawa interaction matrices involving the leftover Higgs scalar from the doublet C.

The model proposed here has characteristic features that are different from other models[11] such as the E_6 superstring-inspired models also with neutral gauge bosons in the 100-GeV to 1-TeV range. For instance, the neutrinos of the Z_2 boson couple to conventional leptonic and hadronic matter with vectorlike couplings and Z_3 has no full strength couplings to the conventional left-handed neutrinos.

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TABLE I. Predictions for the neutral-current couplings and M_{Z_2} for $M_{Z_1} \approx M_{Z^0} = 90$ GeV, $M_{Z_3} \geq 210$ GeV, and $\sin^2\theta_w = 0.22$.

Neutral-current couplings \ M_{Z_2} (GeV)	120	140	160	Experimental values of the neutral-current couplings from Ref. 6
G^u_L	0.38	0.37	0.36	0.339 ± 0.017
G^u_R	−0.12	−0.13	−0.14	-0.172 ± 0.014
G^d_L	−0.40	−0.40	−0.41	-0.429 ± 0.014
G^d_R	0.10	0.10	0.09	$-0.011^{+0.081}_{-0.057}$
G^e_V	0.13	0.08	0.04	-0.044 ± 0.036
G^e_A	−0.50	−0.50	−0.50	-0.498 ± 0.027
C_{1u}	0.20	0.20	0.20	-0.249 ± 0.071
C_{1d}	−0.35	−0.35	−0.35	0.381 ± 0.064
$C_{2u} - \frac{1}{2} C_{2d}$	0.08	0.08	0.07	0.19 ± 0.37

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