Gauged baryon and lepton numbers

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A possible extension of the standard model can be defined by gauging the global baryon- and lepton-number U(1) symmetries. Gauging baryon and lepton numbers provides a natural framework for the seesaw mechanism in the lepton sector, and the Peccei-Quinn mechanism in the quark sector. Another consequence of this extension is that the usual three generations of fermions are not anomaly-free. However, we consider a wider framework involving the existence of generations with exotic $SU(2)_L \otimes U(1)_Y$ quantum numbers. This allows us to "derive" a spectrum of fermions which contain the known quarks and leptons.

There is a widely held view that the only fundamental symmetries are local symmetries. In this paper we examine the possibility that the global U(1) symmetries of baryon (B) and lepton (L) numbers are in fact local symmetries which are spontaneously broken at some scale.[1] If this is the case, then the standard model (SM) gauge group is extended to

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_L \otimes U(1)_B \ . \tag{1}$$

The gauge bosons associated with the gauge symmetries $U(1)_L$ and $U(1)_B$ couple to a lepton number and baryon number, respectively. The lepton and baryon local U(1) symmetries can be broken in many ways. The simplest breaking can be achieved by assuming the existence of two $SU(2)_L \times U(1)_Y$-singlet Higgs bosons H_1, H_2 in addition to the $Y=1$ Higgs doublet ϕ. The Higgs fields H_1 and H_2 contain nonzero lepton and baryon numbers, respectively, while ϕ has zero baryon and lepton numbers. The Higgs fields H_1 and H_2 are responsible for the spontaneous breakdown of lepton and baryon numbers, respectively. The quantum numbers of Higgs bosons are such that there is no mixing of the B and L gauge bosons with the other gauge bosons. The gauge and Higgs sector of the model define a very straightforward extension of the SM.

An interesting possibility is that these Higgs bosons have dual roles. First the Higgs field H_1 responsible for the spontaneous breakdown of lepton number may allow the neutrino to gain a Majorana mass via the seesaw mechanism.[2] Indeed if right-handed neutrinos exist, and H_1 has two units of lepton number, then the model has the field content of the Chikashige-Mohapatra-Peccei (CMP) model[3] [except that there is now no Majoron as the Goldstone boson is absorbed by the $U(1)_L$ gauge boson]. This leads to a natural explanation for the smallness of neutrino masses when right-handed neutrinos are present. Also note that the dual role of H_1 allows us to connect the lepton-number symmetry-breaking scale [the H_1 vacuum expectation value (VEV)] to the mass scale of the neutrinos, m_ν. Clearly $\langle H_1 \rangle \propto \langle \phi \rangle^2 / M_\nu$.

The Higgs fields responsible for the spontaneous breakdown of baryon number, H_2, may also play a dual role in connection with the Peccei-Quinn mechanism for solving the strong CP problem.[4] An interesting invisible-axion model can be defined by adding to the standard model a Higgs singlet and a vectorlike $SU(2)_L \otimes U(1)_Y$-singlet quark field[5] [the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model].

In the KSVZ model $SU(2)_L \otimes U(1)_Y$-singlet quark fields Q_L, Q_R are introduced. We assume that these fields have baryon number B and $U(1)_{PQ}$ numbers $X, -X$, respectively. The introduction of the quark fields Q_L, Q_R leads to an $SU(3)_c^2 U(1)_{PQ}$ anomaly which solves the strong CP problem. One consequence of the assumption that Q_L, Q_R transform as an $SU(2)_L \otimes U(1)_Y$ singlet is that the mass term of these fields can be *a priori* either Dirac or Majorana (or both). An examination of the quantum numbers of Q_L and Q_R shows that a Dirac mass term requires an $SU(2)_L \otimes U(1)_Y$-singlet Higgs boson with two units of PQ charge and zero baryon number. Alternatively, Majorana mass terms require two $SU(2)_L \otimes U(1)_Y$-singlet Higgs fields H_2, H_2', each with two units of baryon number, but one with two units of PQ charge and the other with minus two units of PQ charge. In this latter case involving two Higgs fields, it is possible to define two PQ symmetries (one defined on the Q_L quark field and the other on Q_R quark field) and hence two Goldstone bosons when the symmetries are spontaneously broken. From our point of view, the latter case of Majorana mass terms is interesting because the Higgs fields carry baryon number. A consequence of this is that when the symmetries $U(1)_B \otimes U(1)_{PQ} \otimes U(1)'_{PQ}$ are spontaneously broken (i.e., $\langle H_2 \rangle = v_1$, $\langle H_2' \rangle = v_2$), one of the Goldstone bosons is absorbed by the gauge boson associated with the symmetry $U(1)_B$. This gauge boson gains mass and the orthogonal Goldstone boson is the physical axion. Specifically, the Majorana mass terms arise from the Yukawa Lagrangian

$$\mathcal{L}_{\rm Yuk} = \lambda_1 H_2 \overline{Q}_L (Q_L)^c + \lambda_2 H_2' \overline{Q}_R (Q_R)^c \ , \tag{2}$$

where the superscript c denotes the conjugate field and λ_1, λ_2 are Yukawa couplings. Observe that the existence of Majorana mass terms implies that the $SU(3)_c$ assignment of Q_L, Q_R must be exotic (since $3\otimes 3 \not\supset 1$). The smallest representation $\mathbf{N}$ of $SU(3)_c$ which works (i.e., satisfies $\mathbf{N}\otimes\mathbf{N}\supset 1$) is the $\mathbf{8}$ representation.[6] Since H_2 and H_2' transform nontrivially under $U(1)_B$, it becomes possible to relate the scale of baryon-number breaking to the mass scale of the Q_L quark.

The remainder of this paper considers some implications of the gauge group Eq. (1) with regard to the fermions in the theory. In particular, we will show that some of the simplest "generations" of the gauge group Eq. (1) (i.e., the simplest anomaly-free sets of fermions with lepton-quark symmetry) are compatible with the fermion spectrum which experiments have thus far uncovered.

It is well known that an ordinary generation suffers from triangle gauge anomalies[7] under the U(1) symmetry $B+L$ (although $B-L$ is free from anomalies if right-handed neutrinos exist). It is clear that, within the framework of ordinary generations, the anomalies of B and L can only both be canceled if generations with leptons with lepton number $L=1$ and quarks with $B=\frac{1}{3}$ are paired with generations with opposite lepton number and baryon number, i.e., with leptons with $L=-1$ and quarks with $B=-\frac{1}{3}$. In this paper we will assume that nature does not choose this mirror-type mechanism for canceling the anomalies. Instead we consider the possibility that exotic generations[8,9] are utilized. Exotic $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$ generations with nonstandard $SU(2)_L\otimes U(1)_Y$ quantum numbers can be defined which feature (a) lepton-quark symmetry, (b) particles in the generation which can gain mass with the aid of only an ordinary $Y=1$ Higgs doublet, and (c) anomaly freedom under $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$.

A striking example of an exotic generation is defined by the sequence

$$\begin{aligned}\text{leptons:}\quad & \mathbf{N}_R(Y_l)\oplus(\mathbf{N}-1)_L(Y_l-1)\\ &\oplus(\mathbf{N}-1)'_L(Y_l+1)\oplus(\mathbf{N}-2)_R(Y_l)\,;\\ \text{quarks:}\quad & \mathbf{N}_R(-Y_l/3)\oplus(\mathbf{N}-1)_L(-Y_l/3-1)\\ &\oplus(\mathbf{N}-1)'_L(-Y_l/3+1)\oplus(\mathbf{N}-2)_R(-Y_l/3)\,,\end{aligned}\tag{3}$$

where $\mathbf{N}$ stands for the N-dimensional representation of $SU(2)_L$ and the hypercharges of the multiplets are indicated by the numbers in parentheses. These multiplets of quarks and leptons (or "exotic generations") are free from $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$ triangle anomalies for any $N\geq 2$ and for any Y_l. They are also free from global anomalies.[10] They are trivially free of mixed gravitational triangle anomalies[11] since the exotic generation satisfies $\mathrm{Tr}Y=0$ when summed over the Weyl fermions (this condition is necessary for no massless charged particles). The cancellation is nontrivial for $Y_l\neq 0$ because the $SU(2)_L\otimes U(1)_Y$ anomalies of the quarks cancel with the anomalies of the leptons. Note that if $N=2$ and $Y_l=1$ the generation in Eq. (1) reduces to an ordinary standard-model-like generation (with a right-handed neutrino). Observe that all of the particles can gain mass with only a single Higgs doublet ϕ (and its charge-conjugate doublet $\tilde{\phi}$), via the Yukawa coupling terms $\overline{N}_R(N-1)_L\phi$, $\overline{N}_R(N-1)'_L\tilde{\phi}$, $\overline{(N-1)}'_L(N-2)_R\phi$, $\overline{(N-1)}_L(N-2)_R\tilde{\phi}$. Also note that it is clear from Eq. (3) that there are an infinite number of doublet-type generations (parametrized by Y_l), each with 16 fields.[12]

Under B,L the exotic generation Eq. (3) suffers from triangle anomalies (although $B-L$ is anomaly-free). The $U(1)_L$ charges are assumed to be the number L for leptons (and zero for quarks) and the $U(1)_B$ charges are the number B for quarks and zero for leptons. The triangle anomaly is proportional to $\mathrm{Tr}T^a\{T^b,T^c\}$, where T^a,T^b,T^c are generators of the semisimple gauge group Eq. (1). Under the gauge group Eq. (1), the only potential anomaly arises from $SU(2)^2U(1)_B$ and $SU(2)^2U(1)_L$. The anomalies $U(1)_B^3$ and $U(1)_L^3$ cancel because the B and L quantum numbers are vectorlike. There are also no mixed anomalies such as $U(1)_Y^2U(1)_B$, which follows from the cancelation of the $SU(2)^2U(1)_B$ anomaly and because Q and B are each vectorlike [recall that $Y=2(Q-I_3)$]. For the general exotic generation of the form Eq. (3), the $SU(2)^2U(1)_L$ anomaly is given by

$$\begin{aligned}A(SU(2)^2U(1)_L)=[&Nq(N)-2(N-1)q(N-1)\\ &+(N-2)q(N-2)]L\,,\end{aligned}\tag{4}$$

where $q(N)$ is the group factor defined by $\mathrm{Tr}T^aT^b=Nq(N)\delta^{ab}$, where the generators T^a,T^b are in the N-dimensional representation of $SU(2)_L$. The coefficients $q(N)$ are defined by $q(N)=\frac{1}{12}(N-1)(N+1)$. Substituting $q(N)$ into Eq. (4) we find

$$A(SU(2)^2U(1)_L)=4(N-1)L\,.\tag{5}$$

Similarly we obtain, for $SU(2)^2U(1)_B$,

$$A(SU(2)^2U(1)_B)=12(N-1)B\,.\tag{6}$$

The question now is what are the simplest (i.e., with minimum number of particles) solutions to the anomaly problem? This will define the simplest $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y\otimes U(1)_L\otimes U(1)_B$ "generations." We assume that multiplets specified by the same N have the same L and B (i.e., there is no mirror-type cancellation of the anomalies), but that multiplets with different N's can have L's and B's with opposite sign in Eq. (3). In general if there are α $N=2$ generations, β $N=3$ generations, and γ $N=4$ generations, and so on. Then the anomaly cancellation condition reduces to the equation

$$\alpha\pm 2\beta\pm 3\gamma\pm 4\delta\pm\cdots=0\,.\tag{7}$$

The simplest solutions are $\alpha=2$, $\beta=1$; $\alpha=3$, $\gamma=1$; $\alpha=4$, $\beta=2$. Thus one of the simplest anomaly-free structures of the gauge group $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y\otimes U(1)_L\otimes U(1)_B$ corresponds to four ordinary doublet-type $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$ generations and two exotic triplet $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$ generations. Such a fermion spectrum is consistent with the observed fermions.

The anomaly cancellation does not tell us anything about the hypercharges of the multiplets. The hypercharge assignment $Y_l=1$ for the $N=2$-type generations leads to four standard $SU(3)_c\otimes SU(2)_L\otimes U(1)_Y$ generations of fermions. An interesting assignment for the hypercharge Y_l of the $N=3$ multiplet is $Y_l=2$, which leads to four leptons with charges 2, 1, 1, and 0 and four quarks with charges $\frac{2}{3}$, $-\frac{1}{3}$, $-\frac{1}{3}$, and $-\frac{4}{3}$. The addition of the $N=3$ multiplet with $Y_l=2$ to three $N=2$ multiplets with $Y_l=1$ was examined in some detail in Ref. 9. Furthermore, the analysis of the gauge couplings show that it is possible that the bottom quark may be a member of this multiplet, rather than an $N=2$ doublet. The case under study in Ref. 9 was in the context of the SM gauge group. In this case gauge invariance allowed ordinary-type mixing in the quark sector (i.e., Higgs-boson–quark–quark terms), but vectorlike terms (lepton-lepton terms) could be allowed in the lepton sector. This could in principle be a problem since the vectorlike terms are independent of the Higgs-boson vacuum expectation value, and thus have no natural scale. While small or no mixing is technically natural, it has to be assumed. However, the assignments of L and B of the $N=2$ multiplets and the $N=3$ multiplet imply that the usual quark-quark-Higgs-boson mixing terms are still allowed, while the vectorlike lepton mixing terms must be absent.

Finally we remark that if lepton (baryon) number is gauged and baryon (lepton) number is not then the anomalies can be canceled if the spectrum of fermions consists of four $N=2$-type generations and two leptonlike (quarklike) $N=3$ generations. A leptonlike (quarklike) $N=3$ generation consists of just the leptons (quarks) in Eq. (3) with $Y_l=0$ [$Y_l=0$ is necessary for $SU(2)_L \otimes U(1)_Y$ anomaly cancellation in this case].

In conclusion, we have examined several implications of gauging the B and the L symmetries. Gauging B and L provide a natural framework for the seesaw mechanism in the lepton sector and the Peccei-Quinn mechanism in the quark sector. Furthermore, by allowing for the existence of exotic fermions, we have shown that there exists anomaly-free sets of fermions defined by this gauge group which contain the fermions which have been experimentally discovered thus far.

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