Gauge Theory for Baryon and Lepton Numbers with Leptoquarks

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Models where the baryon (B) and lepton (L) numbers are local gauge symmetries that are spontaneously broken at a low scale are revisited. We find new extensions of the standard model which predict the existence of fermions that carry both baryon and lepton numbers (i.e., leptoquarks). The local baryonic and leptonic symmetries can be broken at a scale close to the electroweak scale and we do not need to postulate the existence of a large desert to satisfy the experimental constraints on baryon number violating processes like proton decay.

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Introduction.—In the standard model (SM) the baryon and lepton numbers are automatic global symmetries of the renormalizable couplings. Nonperturbative quantum effects associated with anomalies break these symmetries but conserve B-L. In order to explain the matter-antimatter asymmetry in the Universe, B-L should be broken if we use the standard scenarios for baryogenesis.

We know that the neutrinos are massive and the lepton number associated with each family of leptons in the SM is not conserved. However, it is possible that total lepton number is a good symmetry in nature. One can add higher-dimensional operators to the SM, e.g., $QQQL/\Lambda_B^2$ and $LLHH/\Lambda_L$, which have their origin in new degrees of freedom that arise at a high scale where the physics is described by a more fundamental theory such as a grand unified theory (GUT). The first of the two operators gives proton decay conserving B-L, and the second one is responsible for Majorana neutrino masses. Unfortunately, in order to satisfy the bounds from proton decay experiments (i.e., $\tau_p > 10^{32-34}$ years) the relevant scale has to be very high, $\Lambda_B > 10^{15}$ GeV (For a review on proton decay in several scenarios for physics beyond the SM, see Ref. [1]). Hence, one needs to postulate the existence of a large desert between the weak scale and the scale Λ_B where one can understand the origin of these interactions.

In the classical approach based on GUTs, one can compute the operators mediating proton decay. Furthermore, making use of the running of the gauge couplings, one understands at which scale the larger gauge group is spontaneously broken to the standard model, and hence, why the scale Λ_B is so large. GUTs make a large number of interesting predictions, but since they unify quarks and leptons into the same multiplets, baryon and lepton number cannot be defined as independent symmetries.

Recently, the authors of Ref. [2] have investigated a different approach in which the baryon and the total lepton numbers are independent local gauge symmetries that can be broken at the low scale. Despite the spontaneous breaking of these symmetries the charges of the fields are such that baryon number violating processes are very suppressed even in the presence of nonrenormalizable interactions. Such models provide a way to understand the suppression of baryon and lepton number violating interactions without the necessity of a large desert. Several authors have studied the possibility of gauging B and L as independent symmetries. See Refs. [2–6] for details (See also Refs. [7–9] for early related studies.). Unfortunately, all the solutions proposed are in disagreement with the recent constraints from the LHC experiments or with cosmological data.

In this Letter, we revisit the possibility of gauging B and L in an anomaly-free theory and spontaneously breaking these gauge symmetries at a low scale (e.g., TeV scale). We find that using what we call leptoquarks one can cancel all anomalies and generate masses for all fields in the theory. In the simplest scenario, there is a fermionic dark matter candidate, whose stability is an automatic consequence of the gauge symmetry. The new fermions in the theory do not induce flavor violation and after symmetry breaking one generates $\Delta L = \pm 2$, ± 3 and $\Delta B = \pm 3$ interactions. Therefore, proton (and baryon number violating neutron) decay is forbidden and there is no need to postulate a large desert.

This Letter is organized as follows: In the section on B and L as local gauge symmetries, we discuss the conditions coming from the cancellation of the baryonic and leptonic anomalies. In the section on fermionic leptoquarks, we discuss in detail how to cancel the anomalies in models with fermionic leptoquarks. The simplest viable model is discussed in the section on the theoretical framework, and we summarize our results in the conclusions section.

B and L as local gauge symmetries.—In the standard model the baryon and lepton numbers are accidental global symmetries of the Lagrangian, but they are not free of anomalies. In order to define a consistent theory where baryon and lepton numbers are local gauge symmetries, all relevant anomalies need to be cancelled. Therefore, the SM particle content has to be extended by additional fermions. In our notation, the SM fermionic fields and their transformation properties under $SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$ are given by

$$Q_L \sim \left(3, 2, \frac{1}{6}, \frac{1}{3}, 0\right), \qquad u_R \sim \left(3, 1, \frac{2}{3}, \frac{1}{3}, 0\right),$$
$$d_R \sim \left(3, 1, -\frac{1}{3}, \frac{1}{3}, 0\right), \quad \ell_L \sim \left(1, 2, -\frac{1}{2}, 0, 1\right),$$
$$\nu_R \sim (1, 1, 0, 0, 1), \qquad e_R \sim (1, 1, -1, 0, 1).$$

Here, we already have included the right-handed neutrinos as part of the SM fermionic spectrum. The purely baryonic anomalies we need to understand are

$$\mathcal{A}_1(SU(3)^2 \otimes U(1)_B), \qquad \mathcal{A}_2(SU(2)^2 \otimes U(1)_B),$$
$$\mathcal{A}_3(U(1)_Y^2 \otimes U(1)_B), \qquad \mathcal{A}_4(U(1)_Y \otimes U(1)_B^2),$$
$$\mathcal{A}_5(U(1)_B), \qquad \mathcal{A}_6(U(1)_B^3).$$

In the SM, the only nonzero values are $\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$. In a similar way, the purely leptonic anomalies are

$$\mathcal{A}_7(SU(3)^2 \otimes U(1)_L), \qquad \mathcal{A}_8(SU(2)^2 \otimes U(1)_L),$$
$$\mathcal{A}_9(U(1)_Y^2 \otimes U(1)_L), \qquad \mathcal{A}_{10}(U(1)_Y \otimes U(1)_L^2),$$
$$\mathcal{A}_{11}(U(1)_L), \qquad \mathcal{A}_{12}(U(1)_L^3),$$

where only two anomalies are nonzero in the SM with right-handed neutrinos, i.e., $\mathcal{A}_8 = -\mathcal{A}_9 = 3/2$. In general, one also has to think about the cancellation of the mixed anomalies

$$\mathcal{A}_{13}(U(1)_B^2 \otimes U(1)_L), \qquad \mathcal{A}_{14}(U(1)_L^2 \otimes U(1)_B),$$
$$\mathcal{A}_{15}(U(1)_Y \otimes U(1)_L \otimes U(1)_B),$$

which, of course, vanish in the SM. Various solutions to the equations which define the cancellation of anomalies were studied in Refs. [2–6].

(1) Sequential family. In Refs. [2,3], a sequential family was proposed, where the new quarks have the baryon number -1 and the new leptons have the lepton number -3. Unfortunately, this solution is ruled out today because the new quarks get mass from the SM Higgs vacuum expectation value (VEV) and change the gluon fusion Higgs production by a factor of 9 [10]. This is in disagreement with the recent LHC results. On top of that, the LHC bounds on the masses of the new quarks are strong, and one has Landau poles for the new Yukawa couplings in the TeV region.

(2) Mirror family. In Refs. [2,3], the possibility to use mirror fermions was considered, too. It suffers from the same problems as a sequential family and is also ruled out.

(3) Vectorlike fermions. To avoid Landau poles close to the electroweak scale, Ref. [5] cancelled anomalies using vectorlike fermions. In this case, anomaly cancellation requires that the difference between the baryon numbers of the new quarks is equal to -1, while the difference between the lepton numbers is -3. See Ref. [5] for more details.

In this setup, the neutrino masses are generated through the type I seesaw and the new charged leptons get mass only from the SM Higgs VEV. Therefore, in this model the lepton number is broken by two units and one does not have proton decay. Unfortunately, the new charged leptons change dramatically the Higgs branching ratio into gammas [11], reducing it by about a factor of 3. This model disagrees with the recent LHC results where the newly discovered boson is SM-like.

One can modify this model by adding a new Higgs boson with a lepton number and generate vectorlike masses for the charged leptons, but one will generate dimension nine operators mediating proton decay, e.g.,

$$\mathcal{O}_9 = c_9 (u_R u_R d_R e_R) S_B S_L^\dagger S_L' / \Lambda^5. \tag{1}$$

Here $S_B \sim (1, 1, 0, -1, 0)$, $S_L \sim (1, 1, 0, 0, -2)$, and $S_L' \sim (1, 1, 0, 0, -3)$. Now, assuming that $c_9 \sim 1$ and the VEVs of the S_B, S_L, and S_L' are around TeV, one finds that $\Lambda \geq 10^{7-8}$ GeV. This means that we still have to postulate half of the desert (using a logarithmic scale) in order to satisfy the proton decay bounds. Of course, we could also assume that c_9 is very small.

(4) Leptoquarks. It is natural to think about cancelling the B and L anomalies adding fermionic leptoquarks. This approach was used in Ref. [6] where the authors introduced the fields $F_L \sim (3, 2, 0, -1, -1)$, $j_R \sim (3, 1, \frac{1}{2}, -1, -1)$, and $k_R \sim (3, 1, -\frac{1}{2}, -1, -1)$. Unfortunately, this model is ruled out by cosmology because one predicts the existence of stable charged fields. In the next section, we will elaborate on different possibilities where one can avoid this problem.

Fermionic leptoquarks.—As mentioned above, there are different ways to cancel all relevant anomalies to gauge B and L. However, it is difficult to write a consistent model which is in agreement with collider data and cosmology without postulating the existence of a large desert. In order to find viable scenarios, we will stick to the particle content listed in Table I, where we use fermionic fields that are singlets or in the fundamental of $SU(2)$. We consider different possibilities for the quantum numbers of the new fields under $SU(3)$.

The $SU(2)^2 \otimes U(1)_B$ anomaly can only be cancelled by a field charged under $SU(2)$, most conveniently by a doublet. We, therefore, fix the $SU(2)$ quantum numbers of the new particles to be similar to a SM family (one $SU(2)$ doublet and two singlets). To not spoil the SM anomaly cancellation, we choose the new fields to be vectorlike under the SM gauge group.

Considering the cancellation of the $SU(2)^2 \otimes U(1)_B$ anomaly, one finds the condition

$$B_1 - B_2 = -\frac{3}{N}, \tag{2}$$

TABLE I. The extra particle content of the model.

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	N	2	Y_1	$B_1 = -(3/2N)$	$L_1 = -(3/2N)$
Ψ_R	N	2	Y_1	$B_2 = +(3/2N)$	$L_2 = +(3/2N)$
η_R	N	1	Y_2	$B_3 = -(3/2N)$	$L_3 = -(3/2N)$
η_L	N	1	Y_2	$B_4 = +(3/2N)$	$L_4 = +(3/2N)$
χ_R	N	1	Y_3	$B_5 = -(3/2N)$	$L_5 = -(3/2N)$
χ_L	N	1	Y_3	$B_6 = +(3/2N)$	$L_6 = +(3/2N)$

and for simplicity we use $B_1 = -B_2$. The same applies to the corresponding leptonic anomaly, and we have

$$L_1 = -L_2 = -\frac{3}{2N}. \tag{3}$$

To cancel the $SU(3)^2 \otimes U(1)_B$ anomaly when $N \neq 1$, one needs to impose the condition

$$2(B_1 - B_2) - (B_3 - B_4) - (B_5 - B_6) = 0. \tag{4}$$

Using

$$B_4 = -B_3 \quad \text{and} \quad B_5 = -B_6, \tag{5}$$

this reduces to

$$2B_1 - B_3 - B_5 = 0, \tag{6}$$

which is most easily cancelled by the choice

$$B_1 = B_3 = B_5. \tag{7}$$

Similarly, a good choice is

$$L_4 = -L_3, \qquad L_5 = -L_6, \quad \text{and} \quad L_1 = L_3 = L_5. \tag{8}$$

Finally, we have to think about the anomalies with weak hypercharge. With the above used assignment of baryon and lepton numbers, $\mathcal{A}_4$ and $\mathcal{A}_{10}$ are always cancelled and do not provide a condition for the hypercharges. From $U(1)_Y^2 \otimes U(1)_B$, we obtain the condition

$$Y_2^2 + Y_3^2 - 2Y_1^2 = \frac{1}{2}. \tag{9}$$

A useful set of solutions for this equation is

$$(Y_1, Y_2, Y_3) \in \left\{\left(\pm\frac{1}{2}, \pm 1, 0\right), \left(\pm\frac{1}{6}, \pm\frac{2}{3}, \pm\frac{1}{3}\right), \left(0, \pm\frac{1}{2}, \pm\frac{1}{2}\right)\right\}. \tag{10}$$

It is easy to check that—using any of these choices—all baryonic and leptonic anomalies are cancelled. Since the new particles are vectorlike with respect to the SM gauge group, the SM anomalies do not pose a problem. Additionally, it can be checked that the $U(1)_L \otimes U(1)_B^2$, $U(1)_L^2 \otimes U(1)_B$, and $U(1)_Y \otimes U(1)_L \otimes U(1)_B$ anomalies are also cancelled. These could be relevant because we deal with particles charged both under $U(1)_B$ and $U(1)_L$.

In order to find the scenarios where one avoids a stable electric charged or colored field, we use as a guideline that the new fields should have a direct coupling to the SM fermions or the lightest particle in the new sector is stable. Now, let us discuss the possible scenarios for different values of N.

(1) $N = 1$. If the new fields do not feel the strong interaction, the only solution which allows for a stable field in the new sector is the one where $Y_1 = \pm 1/2$, $Y_2 = \pm 1$, and $Y_3 = 0$. Then, if the lightest field is neutral, one can have a dark matter candidate. We will discuss this solution in the next section in detail.

(2) $N = 3$. If one uses the weak hypercharges $Y_1 = \pm 1/6$, $Y_2 = \pm 2/3$, and $Y_3 = \pm 1/3$, a stable colored field can be avoided. Unfortunately, in order to generate vectorlike masses for the new fields, one needs a scalar $S_{BL} \sim (1, 1, 0, -1, -1)$, and one generates dimension seven operators mediating proton decay.

(3) $N = 8$. This scenario could be interesting, but in order to couple the new leptoquarks to the SM fermions, we need to include extra colored scalar fields. The most attractive way is to add color octet scalars that let the new fermions couple to leptons. The new colored scalars can decay at one loop to a pair of gluons [12] after spontaneous symmetry breaking because of couplings in the scalar potential. We will not pursue this case further, sticking instead to the simplest possible model where $N = 1$.

Theoretical framework.—Our main goal is to define a consistent anomaly free theory based on the gauge group

$$SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L,$$

that is consistent with experimental and observational constraints and does not need a large desert to satisfy the proton decay bounds. The simplest of the solutions discussed in the last section is the one with colorless fermions. We discuss it in more detail now. The new fermion fields of this model are given in Table I, assuming $N = 1$, $Y_1 = \pm 1/2$, $Y_2 = \pm 1$, and $Y_3 = 0$, and we focus on this choice of hypercharges in the remainder of the Letter. We call these fields leptoquarks even though they do not couple to quarks and leptons because they have baryon and lepton numbers $\pm 3/2$.

(1) Interactions. Using the quantum numbers of the fields, the relevant interactions are:

$$-\mathcal{L} \supset h_1 \bar{\Psi}_L H \eta_R + h_2 \bar{\Psi}_L \tilde{H} \chi_R + h_3 \bar{\Psi}_R H \eta_L + h_4 \bar{\Psi}_R \tilde{H} \chi_L + \lambda_1 \bar{\Psi}_L \Psi_R S_{BL} + \lambda_2 \bar{\eta}_R \eta_L S_{BL} + \lambda_3 \bar{\chi}_R \chi_L S_{BL} + a_1 \chi_L \chi_L S_{BL} + a_2 \chi_R \chi_R S_{BL}^\dagger + \text{H.c.}, \tag{11}$$

with $S_{BL} \sim (1, 1, 0, -3, -3)$. Notice that all interactions proportional to the λ_i couplings generate vectorlike mass terms for the new fermions, while the terms proportional to a_i give us the Majorana masses for the neutral fields.

(2) Majorana neutrino masses. It is very easy to realize the type I seesaw [13] mechanism (even at the weak scale) for neutrino masses including a new Higgs field $S_L \sim (1, 1, 0, 0, -2)$, and as usual we have the interactions

$$-\mathcal{L}_\nu = Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{\lambda_R}{2} \nu_R \nu_R S_L + \text{H.c.} \tag{12}$$

(3) Symmetry breaking. The local baryonic and leptonic symmetries, $U(1)_L$ and $U(1)_B$, are broken by the VEV of S_{BL}, while the VEV of S_L only contributes to the breaking of $U(1)_L$. The fields S_L and S_{BL} can be written as

$$S_L = \frac{1}{\sqrt{2}}(v_L + h_L) + \frac{i}{\sqrt{2}} A_L, \tag{13}$$

$$S_{BL} = \frac{1}{\sqrt{2}}(v_{BL} + h_{BL}) + \frac{i}{\sqrt{2}} A_{BL}. \tag{14}$$

After symmetry breaking the two new physical scalars h_L and h_{BL} mix with each other and with the standard model Higgs boson.

(4) Fermionic sector. After symmetry breaking, in the new sector we have four neutral and four charged chiral fermions, Ψ_a^0 and $\Psi_b^\pm$. It is important to remember that, since the new fermions have a baryon number, they don't couple to the SM fermions and one never generates new sources of flavor violation in the SM quark and lepton sectors.

The lightest fermionic field in the new sector is automatically stable and a candidate for the cold dark matter of the Universe. Notice that the dark matter stability is a consequence of the gauge symmetry, and we do not need to impose any discrete symmetry by hand. It is important to mention that after the breaking of the local $U(1)_L$ and $U(1)_B$ symmetries, we get a Z_2 symmetry as a remnant, which is -1 for all new fermions and $+1$ for the other fields.

The careful study of the properties of this dark matter candidate is beyond the scope of this Letter, but we would like to mention how one can satisfy the direct detection constraints and achieve the right relic density. The dark matter candidate, Ψ_{LF}, couples to the new neutral gauge bosons in the theory, Z_1' and Z_2', and to the new scalars, h_L and h_{BL}, and one can have the right annihilation cross section if we are close to one of these resonances. The direct detection in this case is also through the couplings to the Z and Z_i'. Since we have enough freedom, it is possible to satisfy the direct detection constraints coming from experiments. See Ref. [14] for a recent discussion of the dark matter candidate in models with vectorlike leptons. For the impact of these new fields on the SM Higgs decays and the constraints from electroweak precision observables, see Ref. [14].

(5) Constraints from B and L violating processes. Since the new Higgs field S_{BL} breaks the baryon number in three units, one never generates proton decay. The field S_L breaks the lepton number in two units, so one generates $\Delta L = 2$ Majorana mass terms and we have the usual constraints coming from neutrinoless double beta decay. The lowest-dimensional B and L violating operator, that after symmetry breaking contains just SM fermions, has dimension nineteen

$$\mathcal{O}_{19} = \frac{c_{15}}{\Lambda^{15}} (u_R u_R d_R e_R)^3 S_{BL}. \tag{15}$$

Therefore, B and L violating processes are strongly suppressed even if the cutoff of the theory is quite low.

Summary.—We have proposed a simple extension of the standard model where B and L are gauge symmetries broken at a low scale and nonrenormalizable operators that cause proton decay do not occur. Therefore, there is no need to assume a large desert between the electroweak scale and a scale where additional new physics occurs. Additionally, the new fields needed for anomaly cancellation do not induce new sources of flavor violation and one can have a fermionic candidate for the cold dark matter of the Universe.

A potential difficulty for these models is the generation of a cosmological baryon excess [2,3]. However, it may be possible, by making use of accidental global symmetries of the renormalizable couplings in the model or in other ways, to generate a nonzero baryon asymmetry even though B and L are broken at the low scale.

The scenario studied in this Letter can also be used to understand the absence of large baryon number violating effects in supersymmetric models, where typically one uses the symmetry B-L [15] as a framework to understand this issue at a renormalizable level.

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