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Baryon and lepton number as local gauge symmetries

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We investigate a simple theory where baryon number (B) and lepton number (L) are local gauge symmetries. In this theory B and L are on the same footing and the anomalies are canceled by adding a single new fermionic generation. There is an interesting realization of the seesaw mechanism for neutrino masses. Furthermore, there is a natural suppression of flavor violation in the quark and leptonic sectors since the gauge symmetries and particle content forbid tree level flavor changing neutral currents involving the quarks or charged leptons. Also one finds that the stability of a dark matter candidate is an automatic consequence of the gauge symmetry. Some constraints and signals at the Large Hadron Collider are briefly discussed.

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I. INTRODUCTION

In the standard model (SM) of particle physics baryon number (B) and lepton number (L) are accidental global symmetries. In addition, the individual lepton numbers $U(1)_{L_i}$, where $L_i = L_e, L_\mu, L_\tau$, are also automatic global symmetries of the renormalizable couplings. Since neutrinos oscillate the individual lepton numbers $U(1)_{L_i}$, for a given i, cannot be exact symmetries at the electroweak scale and, furthermore, the neutrinos are massive. At the nonrenormalizable level in the SM one can find operators that violate baryon number and lepton number. For example, $QQQL/\Lambda_B^2$ and $LLHH/\Lambda_L$, where Λ_B and Λ_L are the scales where B and L are broken, respectively [1]. These operators give rise to new phenomena (that are not permitted by the renormalizable couplings) such as proton decay [2] and neutrinoless double beta decay [3].

Baryon number must be broken in order to explain the origin of the matter-antimatter asymmetry in the Universe. Also having Majorana neutrino masses is very appealing since one can explain the smallness of neutrino masses through the seesaw mechanism [4]. Hence, lepton number is also expected to be broken. In the future it may be possible to observe the violation of baryon number and lepton number (For future experimental proposals and current bounds, see Ref. [5].).

In this paper we examine the possibility that B and L are spontaneously broken gauge symmetries where the scale for B and L breaking is low (i.e., around a TeV). Then one does not need a "desert region" between the weak and GUT scales to adequately suppress the contribution of dimension six baryon number violating operators to proton decay [2]. (Note that gauging B-L does not address this issue since the dimension six operators mentioned above are B-L invariant.) In this paper we propose a new model where B and L are gauged and are spontaneously broken at a low scale.

We construct and discuss a simple extension of the standard model based on the gauge symmetry, $SU(3) \times \otimes SU(2) \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$. The anomalies are canceled by adding a single new fermionic generation of opposite chirality, where the new leptons have $L = 3$ and the additional quarks have $B = 1$. In this model we find that there is a natural suppression of flavor violation at tree level in the quark and charged leptonic sectors. The realization of the seesaw mechanism for the generation of neutrino masses is investigated, and we show that the spontaneous breaking of the gauge symmetry does not generate dangerous baryon number violating operators. The model has a dark matter candidate and its stability is an automatic consequence of the gauge symmetry. The most generic signals at the Large Hadron Collider and the relevant constraints are briefly discussed.

II. GAUGING BARYON AND LEPTON NUMBERS

In this section we show how to cancel the anomalies in a simple extension of the standard model theory based on the gauge group $G_{\rm SM} \otimes U(1)_B \otimes U(1)_L$. In this model the SM fields transform as: $Q_L^T = (u, d)_L \sim (3, 2, 1/6, 1/3, 0)$, $l_L^T = (\nu, e)_L \sim (1, 2, -1/2, 0, 1)$, $u_R \sim (3, 1, 2/3, 1/3, 0)$, $d_R \sim (3, 1, -1/3, 1/3, 0)$, and $e_R \sim (1, 1, -1, 0, 1)$ under the gauge group. We add three generations of right-handed neutrinos, $\nu_R \sim (1, 1, 0, 0, 1)$, to the standard model particles above to study the generation of neutrino masses. In order to find an anomaly free theory, one needs to add additional new fermions to cancel the following anomalies (Of course, one has to keep in mind that the anomalies in the SM gauge group should be satisfied as well.):

(1) Baryonic anomalies:

(a) $\mathcal{A}_1(SU(3)^2 \otimes U(1)_B)$: In this case all the quarks contribute and one finds $\mathcal{A}_1^{\rm SM} = 0$.

(b) $\mathcal{A}_2(SU(2)^2 \otimes U(1)_B)$: Since in the SM there is only one quark doublet Q_L for each family, one cannot cancel this anomaly, $\mathcal{A}_2^{\rm SM} = \frac{3}{2}$. Therefore, here one needs extra states in a nontrivial representation of $SU(2)$.

(c) $\mathcal{A}_3(U(1)_Y^2 \otimes U(1)_B)$: In the Abelian sector one has the contributions of all quarks and one finds $\mathcal{A}_3^{\rm SM} = -\frac{3}{2}$.

(d) $\mathcal{A}_4(U(1)_Y \otimes U(1)_B^2)$: In this case, since all SM quarks have the same baryon number, this anomaly is equivalent to the $U(1)_Y$ anomaly condition in the SM, i.e. $\mathcal{A}_4^{\rm SM} = 0$.

(e) $\mathcal{A}_5(U(1)_B)$: The baryon-gravity anomaly is also canceled in the SM, $\mathcal{A}_5^{\rm SM} = 0$.

(f) $\mathcal{A}_6(U(1)_B^3)$: In this case, one finds that this anomaly is zero in the SM, $\mathcal{A}_6^{\rm SM} = 0$.

(2) Leptonic anomalies:

(a) $\mathcal{A}_7(SU(2)^2 \otimes U(1)_L)$: It is easy to show that $\mathcal{A}_7^{\rm SM} = 3/2$.

(b) $\mathcal{A}_8(U(1)_Y^2 \otimes U(1)_L)$: As in the previous case, in the SM this anomaly is not zero, $\mathcal{A}_8^{\rm SM} = -3/2$.

(c) $\mathcal{A}_9(U(1)_Y \otimes U(1)_L^2)$: In the SM this anomaly is canceled.

(d) $\mathcal{A}_{10}(U(1)_L)$: The lepton-gravity anomaly is canceled since we add three families of right-handed neutrinos, $\nu_R \sim (1, 1, 0, 0, 1)$.

(e) $\mathcal{A}_{11}(U(1)_L^3)$: As in the previous case, this anomaly is canceled once we add three families of right-handed neutrinos.

We have to cancel all the anomalies discussed above (and not induce standard model gauge anomalies as well) in order to find an anomaly-free theory with B and L gauged. For a previous study of these anomalies, see Ref. [6].

There are two simple ways to cancel the anomalies. They are:

(i) Case 1: All baryonic anomalies are canceled adding new quarks, $Q_L'^T = (u', d')_L \sim (3, 2, 1/6, -1, 0)$, $u_R' \sim (3, 1, 2/3, -1, 0)$, and $d_R' \sim (3, 1, -1/3, -1, 0)$, which transform as the SM quarks but with baryon number, $B = -1$. At the same time the leptonic anomalies are canceled if one adds new leptons $l_L'^T = (\nu', e')_L \sim (1, 2, -1/2, 0, -3)$, $e_R' \sim (1, 1, -1, 0, -3)$ and $\nu_R' \sim (1, 1, 0, 0, -3)$. All anomalies in the SM gauge group are canceled since we have introduced one new full family. It differs from the usual standard model families since the new quarks have baryon number minus one and the new leptons have lepton number minus three [7].

(ii) Case 2: The baryonic anomalies are canceled adding new quarks, $Q_R'^T = (u', d')_R \sim (3, 2, 1/6, 1, 0)$, $u_L' \sim (3, 1, 2/3, 1, 0)$, and $d_L' \sim (3, 1, -1/3, 1, 0)$, which transform as the SM quarks of opposite chirality but with baryon number, $B = 1$. At the same time the leptonic anomalies are canceled if one adds new leptons $l_R'^T = (\nu', e')_R \sim (1, 2, -1/2, 0, 3)$, $e_L' \sim (1, 1, -1, 0, 3)$ and $\nu_L' \sim (1, 1, 0, 0, 3)$. All anomalies in the SM gauge group are canceled since we have introduced one new full family but with opposite chirality. It also differs from the usual standard model families since the new quarks have baryon number one and the new leptons have lepton number three.

These are the two simplest fermionic contents that give an anomaly-free theory with gauge group $SU(3) \otimes SU(2) \times \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$. For the study of the phenomenological properties of models with an extra generation, see Ref. [9].

III. MASS GENERATION AND FLAVOR VIOLATION

A. Quark sector

We begin by considering the case (1), new generation where the chirality is the same as in the standard model generations. Masses for the new quarks present in the model are generated from their couplings to the SM Higgs:

$$-\Delta\mathcal{L}^{(1)}_{q'\rm mass} = h_U' \bar{Q}_L' \tilde{H} u_R' + h_D' \bar{Q}_L' H d_R' + \text{H.c.}, \qquad (1)$$

where $H \sim (1, 2, 1/2, 0, 0)$ is the SM Higgs, and $\tilde{H} = i\sigma_2 H^*$.

To avoid having a stable colored particle we couple the SM fermions to the new fourth generation quarks. However, at the same time it is important to avoid tree level flavor changing neutral currents in the quark sector. We achieve this goal by adding a new scalar field $\phi \sim (1, 2, 1/2, 4/3, 0)$, which does not get a vev. The interactions of this scalar are $Y_1 \bar{Q}_L' \tilde{\phi} u_R$ + H.c., which permit the new fourth generation quarks to decay to a scalar and a standard model quark. One might think that this particle is the dark matter. Unfortunately, it is not consistent with experiment [10] to have the ϕ^0 be the dark matter because of the mass degeneracy of the imaginary and real parts [11].

Next we consider case (2), where the new fermions have the opposite chirality to the standard model. We shall see that in this case there is a dark matter candidate. Now, mass for the new quarks is generated through the terms,

$$-\Delta\mathcal{L}^{(2)}_{q'\rm mass} = Y_U' \bar{Q}_R' \tilde{H} u_L' + Y_D' \bar{Q}_R' H d_L' + \text{H.c.}. \qquad (2)$$

Decays of the new quarks are induced by adding a new scalar field X with gauge quantum numbers $X \sim (1, 1, 0, -2/3, 0)$, and the following terms occur in the Lagrange density:

$$-\Delta\mathcal{L}_{\rm DM} = \lambda_Q X \bar{Q}_L Q_R' + \lambda_U X \bar{u}_R u_L' + \lambda_D X \bar{d}_R d_L' + \text{H.c.}. \qquad (3)$$

The field X does not get a vev, and so there is no mass mixing between the new exotic generation quarks and the standard model ones. When X is the lightest new particle with baryon number, it is stable. This occurs because the model has a global $U(1)$ symmetry where the Q_R', u_L', d_L', and X get multiplied by a phase. This $U(1)$ symmetry is an automatic consequence of the gauge symmetry and the particle content. Notice that the new fermions have $V + A$ interactions with the W-bosons. The X particle is a dark matter candidate and its properties will be investigated in a future publication. Since case (2), where the quarks have the opposite chirality, has a natural dark matter candidate, we restrict our attention to that model for the remainder of this paper.

The field X has flavor changing couplings that cause transitions between quarks with baryon number 1 and the usual quarks with baryon number 1/3. However, since there is no mass mixing between these two types of quarks integrating out the X does not generate any tree-level flavor changing neutral currents for the ordinary quarks. Those first occur at the one-loop level.

B. Leptonic sector

The interactions that generate masses for the new charged leptons are

$$-\Delta\mathcal{L}_l = Y_E' \bar{l}_R' H e_L' + \text{H.c.} \tag{4}$$

while for the neutrinos they are

$$-\Delta\mathcal{L}_\nu = Y_\nu' l'^T \tilde{H} \nu' + Y_\nu l_L H \nu^C + \frac{\lambda_a}{2} \nu^C S_L \nu^C + \lambda_b \nu^C S_L^\dagger \nu' + \text{H.c.}, \tag{5}$$

where $\nu^C = (\nu_R)^C$, $l' = (l_R')^C$, and $S_L \sim (1, 1, 0, 0, 2)$ is the Higgs that breaks $U(1)_L$, generating masses for the right-handed neutrinos and the quark-phobic Z_L'. We introduce the notation $N = (\nu_R')^C$. After symmetry breaking the mass matrix for neutrinos in the left-handed basis, (ν, N, ν', ν^C), is given by the eight by eight matrix

$$\mathcal{M}_N = \begin{pmatrix} 0 & 0 & 0 & M_D \\ 0 & 0 & M_D' & 0 \\ 0 & (M_D')^T & 0 & M_b \\ M_D^T & 0 & M_b^T & M_a \end{pmatrix}. \tag{6}$$

Here, $M_D = Y_\nu v_H/\sqrt{2}$ and $M_a = \lambda_a v_L/\sqrt{2}$ are 3×3 matrices, $M_b = \lambda_b v_L^*/\sqrt{2}$ is a 1×3 matrix, $M_D' = Y_\nu' v_H/\sqrt{2}$ is a number and $\langle S_L \rangle = v_L/\sqrt{2}$. Let us assume that the three right-handed neutrinos ν^C are the heaviest. Then, integrating them out generates the following mass matrix for the three light-neutrinos:

$$\mathcal{M}_\nu = M_D M_a^{-1} M_D^T. \tag{7}$$

In addition, a Majorana mass M' for the fourth generation right-handed neutrino N,

$$M' = M_b M_a^{-1} M_b^T, \tag{8}$$

is generated. Furthermore, suppose that $M' << M_D'$, then the new fourth generation neutrinos ν' and N are quasi-Dirac with a mass equal to M_D'. Of course we need this mass to be greater than $M_Z/2$ to be consistent with the measured Z-boson width. In this model we have a consistent mechanism for neutrino masses which is a particular combination of Type I seesaws [4].

The vev of the field S_L breaks $U(1)_L$, and one has the usual symmetry breaking mechanism of the SM. In order to complete the discussion of symmetry breaking we introduce a new Higgs S_B with nonzero baryon number (but no other gauge quantum numbers) which gets the vev v_B breaking $U(1)_B$ and giving mass to the leptophobic Z_B'. In summary, the Higgs sector is composed of the SM Higgs, H, S_L, S_B, and X. This is the minimal Higgs sector needed to have a realistic theory where B and L are both gauged, and have a DM candidate.

IV. FLAVOR VIOLATION AND SIGNALS AT THE LHC

(i) Flavor violation:
Even though there are no quark flavor changing neutral currents at tree level, they do occur at the one-loop level. The scalar X is used to couple the fourth generation quarks to the ordinary ones, and we find that at one loop there are box diagrams that give contributions (after integrating out the heavy particles) to the effective Lagrangian for $K - \bar{K}$ mixing of the form, $\lambda^4 \bar{d}_{L,R} \gamma^\mu s_{L,R} \bar{d}_{L,R} \times \gamma_\mu s_{L,R}/(16\pi^2 M^2) + \text{H.c.}$, where the product of the four elements of the Yukawa matrix λ_i (and CKM angles) that enter into the coefficient are denoted by λ^4, and M denotes a mass scale set by the masses of the new fields in the loop. For M of order 100 GeV this is negligible, provided $\lambda < 10^{-2}$.
Charged lepton neutral currents are induced at one-loop level. For example, there is a one-loop contribution to the amplitude for $\mu \to e\gamma$. It involves the usual factor of the muon mass and one-loop suppression factor. In addition, it requires two factors of the mixing between the essentially massless ordinary neutrinos and the new fourth generation neutrino. In the limit we discussed above, where the fourth generation neutrino is quasi-Dirac, this mixing is small.

(ii) Z_L and Z_B:
In this model one can observe lepton number violating processes at the LHC through the channels with same-sign dileptons: $pp \to Z_L^* \to \nu_R \nu_R \to W^\pm W^\pm e_i^\mp e_j^\mp$. However, for this Drell-Yan production one needs the mixing between Z and Z_L, or Z_L and Z_B. One can also have pair production of Z_L through its couplings to the physical Higgses. For a study of these channels see Ref. [12]. In the case of the leptophobic Z_B its coupling to the third generation of quarks can be used to observe it at the LHC. In particular, the channel: $pp \to Z_B^* \to t\bar{t}$. For previous studies of a leptophobic Z', see Ref. [13]. For a

review on the properties of new $U(1)$ gauge bosons see, for example, Ref. [14].

(iii) Decays of the new quarks:
As we have discussed above, to avoid a stable colored particle we introduced the new interactions in Eq. (3). Now we discuss signals at the LHC coming from these interactions. Here we will focus on the case where the new quarks can decay into X and the top quark. Then, one can have the interesting channel: $pp \to \bar{t}' t' \to XX\bar{t}t$. Since X is stable, the final state has missing energy and a $t\bar{t}$ pair (After posting the first version of this article the paper [15] appeared.).

(iv) Baryon number violating processes:
Since baryon number is spontaneously broken it is important to consider possible baryon number violating operators that might arise after symmetry breaking. Using the minimal Higgs sector discussed above, one can see that the operator $QQQL/\Lambda_B^2$ is never generated since we do not have a Higgs which carries B and L quantum numbers. Also, in general we expect the $\Delta B = 2$ operators only when S_B has $B = 2$, but in general we do not induce this operator as well. Hence the model we have introduced does not give rise to dangerous baryon number operators. At the same time, in order to avoid the vev for X, one should forbid the terms with an odd power of X in the scalar potential. Then, one must impose the condition $B(S_B) \neq \pm 2/3, \pm 1/3, \pm 2/9, \pm 2$.

(v) Other aspects:
It is well known, that in any model with an extra fermionic generation one finds that the gluon fusion cross section for the SM Higgs is larger by a factor 9. See, for example, Ref. [16]. However, the new results from CDF and D0 [17] do not rule out our model when the Higgs mass is $114\ \text{GeV} < M_H < 120\ \text{GeV}$, or when $M_H > 200$ GeV. Notice that for a large mixing between H and the singlets S_L and S_B one can relax those constraints. For the study of other aspects, such as electroweak precision constraints, see, for example, Ref. [16].

V. SUMMARY

We have constructed and investigated a simple theory where baryon (B) number and lepton (L) number are local gauge symmetries. In this theory, B and L are treated on the same footing, anomalies are canceled by adding a single new fermionic generation, there is a simple realization of the seesaw mechanism for neutrino masses and there is a natural suppression for flavor violation at tree level in the quark and leptonic sectors. It is important to emphasize that in this theory the B and L violation scales can be as low as TeV and one does not have dangerous processes, such as proton decay. Also one finds that the stability of a dark matter candidate is an automatic consequence of the gauge symmetry. Constraints and signals at the Large Hadron Collider have been briefly discussed. The results of our paper can be applied to different theories for physics beyond the standard model, such as the minimal supersymmetric standard model, where new interactions can give rise to fast proton decay.

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