

Baryon and Lepton Numbers: Life in the Desert¹

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Abstract. The simplest theories where we can understand the origin of the baryon and lepton number violating interactions are discussed. We discuss the desert hypothesis in particle physics and the different scenarios where there is no need to assume it. It is shown that the minimal supersymmetric B-L theory predicts lepton number violation at the Large Hadron Collider if supersymmetry is realized at the low scale. We present the BLMSSM where both symmetries, B and L, can be spontaneously broken at the TeV scale.

1. Introduction

It is well-known that in physics beyond the Standard Model (SM) very often one has to think about the violation of two SM symmetries, Baryon (B) and Lepton (L) numbers, and postulate the existence of a large desert between the low and high scales. It was pointed out by S. Weinberg [1] long time ago that one can write down operators such as, $\mathcal{O}_5 = c_\nu LLHH/\Lambda$, and $\mathcal{O}_6 = c_{BL} QQQL/\Lambda^2$, where the first one breaks total lepton number and the second operator violates both symmetries. Typically, one can compute the coefficient in front of these operators in a grand unified theory defined at the high scale. The scale Λ in \mathcal{O}_6 has to be very large, i.e. $\Lambda > 10^{14-16}$ GeV, in order to satisfy the bounds on the proton decay lifetime. See Fig.1 for a cartoon illustration of the desert hypothesis in particle physics.

If low energy supersymmetry is realized in nature the desert picture is different since at the TeV or multi-TeV scale we can have for example the Minimal Supersymmetric Standard Model (MSSM). In this case one can even predict the unification of gauge couplings at the unified scale, $M_{GUT} \approx 10^{16}$ GeV, if the desert hypothesis is true. See Fig.2 for a possible illustration of the desert picture in the case when we have Supersymmetry. Unfortunately, in this case one has to face the fact that there are new interactions allowed by the SM gauge symmetry which violate B or L at the renormalizable level. These interactions are the well-known R-parity breaking interactions: $\hat{L}\hat{H}_u$, $\hat{Q}\hat{L}\hat{d}^c$, $\hat{L}\hat{L}\hat{e}^c$, and $\hat{u}^c\hat{d}^c\hat{d}^c$.

The main goal of this review is to discuss the possible origin of the B and L violating interactions in the Minimal Supersymmetric Standard Model and show the possibility to define a simple theory where one can have the spontaneous breaking of B and L at the low scale.

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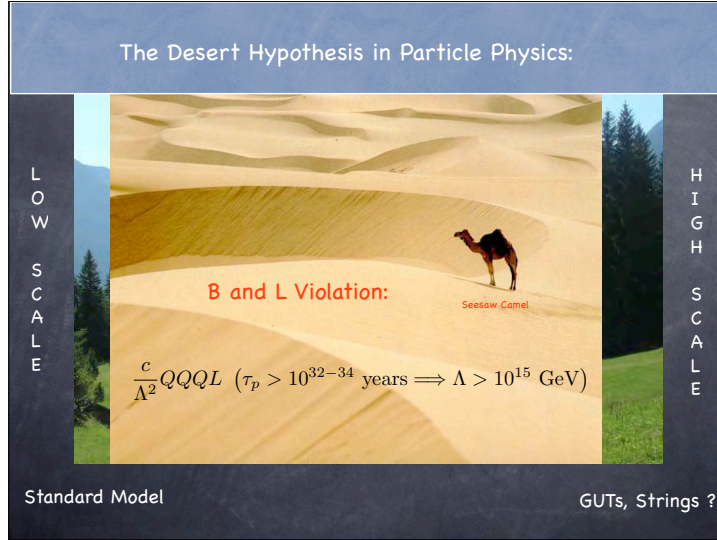


Figure 1. Desert Hypothesis in Particle Physics.

Therefore, in this case there is no need to postulate of the existence of a large desert. One has to say that the most of the people in the particle physics community got used to the idea of having a desert. In my opinion, it is hard to believe that there is no new physics between the low and high scales, and the fact that the people got used to it does not mean that this idea is true.

What do we know about experimental evidences for B and L violation? Unfortunately, after many experimental efforts still there is no direct evidences in a low energy process for the violation of baryon number. As it is well-known, many experimental collaborations have been looking for proton decay signals (a $\Delta B = 1$ and $\Delta L = \text{odd}$ process) and today the lower bounds on the proton decay lifetimes are very impressive. See Fig.3 for a summary of the proton decay lifetime bounds from different collaborations and Ref.[3] for a review on proton decay. An interesting process where B must be broken in two units is $n - \bar{n}$ oscillation. In this case the bounds on the lifetime for free neutron oscillations are very weak, $\tau_{n-\bar{n}} > 10^8 \text{ s}$ [4]. There is a second $\Delta B = 2$ process which can be used to set relevant constraints on new physics scenario, the di-nucleon decay $p p \rightarrow K^+ K^+$. Recently, a new bound has been found in Ref. [5] and the current lower bound is $\tau_{pp \rightarrow K^+ K^+} > 1.7 \times 10^{32} \text{ years}$. What about lepton number violation?. We know from neutrino oscillation experiments that the lepton number defined for each SM family is broken in nature, but still the total lepton number could be conserved. There are many experimental searches for neutrinoless double beta decay. In this case the total lepton number must be broken in two units and if it is discovered we can know about the Majorana nature of the neutrinos. For a review on neutrinoless double beta decay see Ref. [6]. Then, what do we know from cosmology?. It is well-known that in order to explain the baryon asymmetry in the universe we need to have baryon number violation. Therefore, even if there is no a direct connection between the low energy processes mentioned above and the baryogenesis mechanism, we expect baryon number violating processes in nature.

2. B and L in the Superworld

We have mentioned before that in the context of Supersymmetry we have interactions which break B and L at the renormalizable level and dimension five operators which give rise to proton

decay:

$$\mathcal{W}_{BL} = \epsilon \hat{L} \hat{H}_u + \lambda \hat{L} \hat{L} \hat{e}^c + \lambda' \hat{Q} \hat{L} \hat{d}^c + \lambda'' \hat{u}^c \hat{d}^c \hat{d}^c \quad (1)$$

$$+ \frac{c_\nu}{\Lambda} \hat{L} \hat{L} \hat{H}_u \hat{H}_u + \frac{c_L}{\Lambda} \hat{Q} \hat{Q} \hat{Q} \hat{L} + \frac{c_R}{\Lambda} \hat{u}^c \hat{d}^c \hat{u}^c \hat{e}^c. \quad (2)$$

The main difference between the terms in the first and second lines in this equation is that only the first interactions break matter parity. Matter parity is defined as $M = (-1)^{3(B-L)}$, being -1 for all matter chiral superfields and $+1$ for all other superfields. Let us discuss some possible scenarios where these interactions could play a role. The possibility to generate Majorana neutrino masses through the bilinear interaction, $\hat{L} \hat{H}_u$, has been studied by many groups. See for example Ref.[7] for a detailed analysis. A second scenario which give us very fast proton decay corresponds to the case when we combine the interactions $\hat{Q} \hat{L} \hat{d}^c$ and $\hat{u}^c \hat{d}^c \hat{d}^c$. In this case one has the so-called dimension four contributions to nucleon decay. If the relevant coefficients are of order one and the sfermion masses are at the TeV scale the lifetime of the proton is too short, $\tau_p \sim 10^{-20}$ years. Therefore, one has two options: a) we assume small couplings, $\lambda' \lambda'' < 10^{-26}$, or b) we try to understand the origin of these interactions to see if they are suppressed. It is important to mention that even if renormalizable interactions are absent still we get severe constraints on the dimension five operators mediating proton decay. See Ref.[3] for a detailed discussion.

Now, let us focus on the first goal and try to understand the origin of the B and L violating interactions at the renormalizable level. We have mentioned that these interactions break M-parity and of course B-L. Therefore, if we define a theory where B-L is conserved at the scale Λ_{B-L} these interactions are not allowed before symmetry breaking and once we break the symmetry we can understand the size of these interactions. This idea has been studied by many different groups [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. We investigated this issue for the first in Ref. [16] where we defined the simplest supersymmetric left-right model. In this case the only way to break the gauge symmetry $SU(2)_R \otimes U(1)_{B-L}$ to $U(1)_Y$ is to give a vacuum expectation value to the right-handed sneutrinos. Therefore, one can say that the minimal supersymmetric left-right model predicts that R-parity should be spontaneously broken and one expects lepton

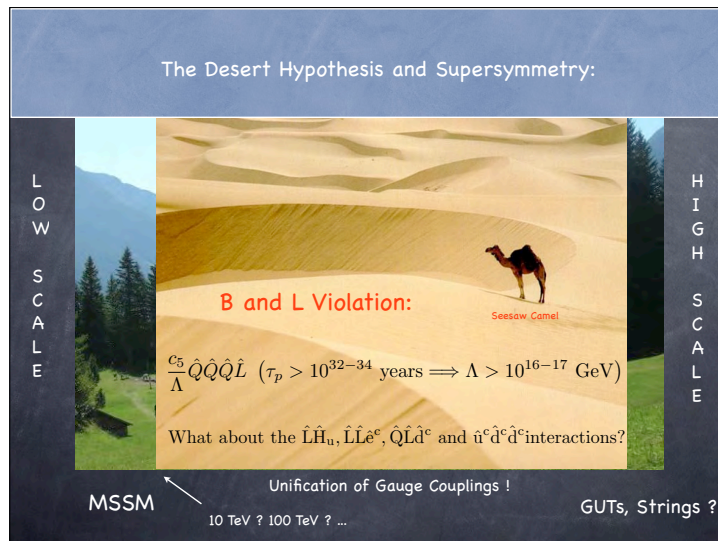


Figure 2. Supersymmetry and the Desert Hypothesis.

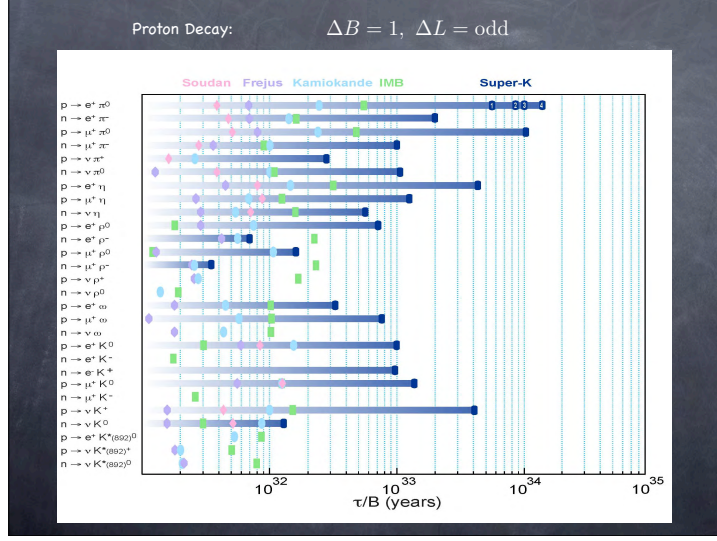


Figure 3. Proton decay bounds [2].

number violating signals at the Large Hadron Collider. In this short review I will discuss mainly the simplest supersymmetric theory which predicts spontaneous breaking of R-parity and lepton number violation at the TeV scale.

3. The Minimal Gauged $U(1)_{B-L}$ Model with Spontaneous R-parity Violation

We have mentioned before that if we want to understand the possible origin of the lepton and baryon number violating interactions in the MSSM one has to define a theory where B-L is part of the gauge symmetry. Now, the simplest theory was proposed in Ref.[17] and here we discuss the main features and predictions:

- This theory is based on the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$.
- The main prediction is that R-parity must be broken.
- The only needed extra matter fields with B-L quantum numbers are the right-handed superfields.
- The B-L and R-parity breaking scales are defined by the SUSY breaking scale.
- One predicts lepton number violation at the LHC.
- The theory predicts two light sterile neutrinos below the eV scale.

The superpotential of this theory is very simple, one has the MSSM superpotential and an extra Yukawa interaction for the neutrinos,

$$\mathcal{W}_{B-L} = \mathcal{W}_{RpC} + Y_\nu \hat{L} \hat{H}_u \hat{\nu}^c, \quad (3)$$

where

$$\mathcal{W}_{RpC} = Y_u \hat{Q} \hat{H}_u \hat{u}^c - Y_d \hat{Q} \hat{H}_d \hat{d}^c - Y_e \hat{L} \hat{H}_d \hat{e}^c. \quad (4)$$

The new soft terms relevant for our discussion are given by

$$V_{soft} \supset M_{\tilde{\nu}^c}^2 |\tilde{\nu}^c|^2 + (A_\nu \tilde{L} H_u \tilde{\nu}^c + \text{h.c.}). \quad (5)$$

Now, in order to break the extra gauge symmetry, B-L, there is only one solution: *The right-handed sneutrino must get a vacuum expectation value !*

It is very easy to show how the right-handed sneutrino gets a VEV. We compute the scalar potential and from the minimization conditions one finds

$$v_R^2 = -8 \frac{M_{\tilde{\nu}^c}^2}{g_{BL}^2}, \quad (6)$$

where $M_{\tilde{\nu}^c}^2$ has to be negative. It has been shown in Ref. [18] that it is very easy to have a realistic spectrum for all sfermions in the theory. As one can expect the sfermion masses have a new contribution from the B-L D-term and typically the left-handed sleptons should be lighter if the soft mass for all the particles are similar at the TeV scale.

The neutrino spectrum in this theory is quite peculiar, it is easy to prove that only one of the right-handed neutrinos get a large mass around TeV scale and the rest are light. Therefore, one can have a 3 + 2 system with masses below the eV scale. See Refs. [10, 20, 21] for the detailed analysis. One can think about the possible new contributions coming from proton decay in this theory. Using the lepton number violating interactions above and the terms coming from the higher-dimensional operator $\hat{u}^c \hat{d}^c \hat{d}^c \hat{\nu}^c / \Lambda_B$ one finds new contributions to proton decay [18] but assuming a large cutoff, around the GUT scale, one can satisfy the experimental bounds on the proton decay lifetime. Notice that here one needs to assume again a large desert from the TeV scale to the GUT scale.

This theory makes very interesting predictions for the LHC because the B-L symmetry is broken at the TeV scale and one has lepton number violating signals. Therefore, in order to test this theory one needs to look for the B-L gauge boson, identify the signals from the supersymmetric particles but in this case there is no missing energy signals associated to a stable LSP because R-parity is broken. We have investigated the most striking signals from this theory in Ref. [18] where we have pointed out the properties of the channels with four leptons, three of them with the same electric charge, and four jets. See Fig.4 for the topology of these signals and Ref. [18] for the detailed analysis of these signals at the LHC. Before we finish this

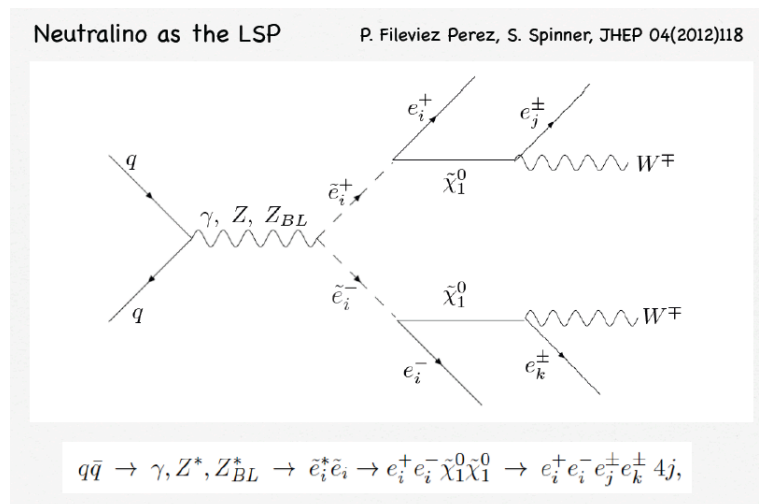


Figure 4. Lepton Number Violating Signals [18].

section let us mention the main idea behind the simplest theory for R-parity conservation. In order to write down a simple theory where local B-L is broken to matter parity, we need to

go beyond the minimal model discussed above and add extra Higgses. Since the right-handed neutrinos are present in the theory we always have the vacuum which corresponds to their vacuum expectation value. Therefore, we need to assume that only the extra Higgses with an even number of B-L break the gauge symmetry. See also Ref. [22, 23] for the application of the Stueckelberg mechanism in this context. Unfortunately, in the context of grand unified theories we cannot find a simple scenario for R-parity conservation. It is well-known that in SUSY $SU(5)$ we need to impose matter parity by hand as in the MSSM, and in the context of $SO(10)$ we need huge representations to achieve R-parity conservation. Therefore, one can say that there is no a simple scenario based on GUTs for R-parity conservation. Here, we would like to emphasize again that the minimal supersymmetric theory based on B-L makes a hard prediction: R-parity must be spontaneously broken and one expects striking lepton number violating signals at the LHC if supersymmetry is realized at the low scale.

4. Life in the Desert: Breaking B and L at the TeV scale

We have discussed the possibility to understand the origin of the lepton and baryon number violating interactions present in the MSSM at the renormalizable level. Unfortunately, in this case one needs to assume a large cutoff in order to satisfy the bounds on the proton decay lifetime. Here we will discuss a different theory where B and L can be broken at the TeV scale and there is no need to assume a desert.

In order to prove that B and L can be broken at the low scale we can define a theory where we have two extra local symmetries. Then, the theory is based on $G_{SM} \otimes U(1)_B \otimes U(1)_L$ [24] where G_{SM} is the gauge group of the Standard Model. We refer to this model as “BLMSSM”. The main features of this theory are:

- The baryon and lepton numbers are local symmetries broken at the SUSY scale.
- In order to cancel all anomalies we add a vector-like generation which is composed of \hat{Q}_4 , \hat{u}_4^c , \hat{d}_4^c , \hat{L}_4 , \hat{e}_4^c , $\hat{\nu}_4$, and \hat{Q}_5^c , \hat{u}_5 , \hat{d}_5 , \hat{L}_5^c , \hat{e}_5 , $\hat{\nu}_5$. Here the baryon and lepton numbers of the new chiral superfields are different since one has to satisfy the conditions $B_{Q_4} + B_{Q_4^c} = -1$ and $\ell_{L_4} + \ell_{L_4^c} = -3$.
- In order to break the local baryonic symmetry and generate vector-like masses for the extra quarks we need to add new Higgses. In this case we need to have for example the term $\hat{Q}_4 \hat{Q}_4^c \hat{S}_B$. Therefore, this term defines the baryonic quantum number of $\hat{S}_B \sim 1$, and we have $\hat{\tilde{S}}_B \sim -1$. As we pointed out in Ref. [24] one cannot avoid the operator $\hat{u}^c \hat{d}^c \hat{d}^c \hat{S}_B / \Lambda_B$, and after symmetry breaking one has baryon number violating interactions which can be suppressed by the cutoff of the theory.
- In the leptonic sector the situation is more involved since one can have different scenarios:
 - a) In the first case if one sticks to the seesaw mechanism the new Higgses should have an even leptonic number, $\hat{S}_L, \hat{\tilde{S}}_L \sim \pm 2$. The new leptons have only chiral masses and there is no proton decay after symmetry breaking because all the interactions violate the total lepton number in an even number. This case was investigated in details in Ref. [24] and Ref. [25].
 - b) One can generate vector-like masses for the new leptons, $\hat{L}_5^c \hat{L}_4 \hat{S}_L$, if the Higgses $\hat{S}_L, \hat{\tilde{S}}_L \sim \pm 3$. In this case one gets operators mediating proton decay since $|\Delta B| = 1$ and $|\Delta L| = 3$. One of the operators that mediate proton decay in this case has dimension eleven, $\hat{Q} \hat{Q} \hat{Q} \hat{L} (\hat{L} \hat{H}_u)^2 \hat{S}_B \hat{\tilde{S}}_L / \Lambda^7$. Therefore, the cutoff scale in this case does not need to be very large.
- There is no extra flavour violation at tree level because the new fermions do not mix with the SM fermions.
- There is no Landau pole at the low scale.

It is important to mention that in the context of the BLMSSM one could modify the LHC bounds on the supersymmetric particles because one has baryon number violation at the low scale. We have investigated in detail the impact of the new fermions on the Higgs mass [26] and decays in Ref. [25].

5. Summary

We have discussed in a general way the need to postulate a desert between the low and high scales in order to satisfy the bounds on the proton decay lifetime. In the first part of this review we have shown that the minimal supersymmetric B-L theory predicts that R-parity should be spontaneously broken and one expects lepton number violation at the LHC. The simplest scenarios for the conservation of R-parity were briefly discussed. It has been mentioned that there is no simple grand unified theory defined in four dimensions where we understand the conservation of R-parity. A simple theory where there is no need for a desert has been discussed. In this case B and L can be broken at the low scale and we do not get any operator mediating proton decay. It is important to emphasize that the two scenarios discussed here can be realized at the TeV scale and one can have very interesting supersymmetric signals at the Large Hadron Collider.

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