



# Multiplicative conservation of baryon number and baryogenesis

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## Abstract

In the canonical seesaw mechanism of neutrino mass, lepton number is only multiplicatively conserved, which enables the important phenomenon of leptogenesis to occur, as an attractive explanation of the present baryon asymmetry of the Universe. A parallel possibility, hitherto unrecognized, also holds for baryon number and baryogenesis. This new idea is shown to be naturally realized in the context of a known supersymmetric string-inspired extension of the Standard Model, based on  $E_6$  particle content, and having an extra  $U(1)_N$  gauge symmetry. Within this framework, two-loop radiative neutrino masses are also possible, together with a new form of very long-lived matter.

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The Universe has an imbalance of matter over antimatter, called the baryon asymmetry [1]. An elegant way of understanding this is the phenomenon of leptogenesis [2,3], by which a lepton asymmetry is established from the decays of heavy Majorana singlet fermions  $N_i$  and gets converted [4] into a baryon asymmetry through sphalerons [5] during the electroweak phase transition in the early Universe. In this scenario, lepton number is only multiplicatively conserved and neutrinos acquire small Majorana masses through the famous canonical seesaw mechanism [6].

In this Letter, a parallel and equally elegant possibility, i.e., multiplicatively conserved baryon number and baryogenesis, is proposed and shown to be naturally realized in the framework of a known supersymmetric string-inspired extension [7] of the Standard Model (SM), as detailed below.

In leptogenesis, the only interactions of  $N_i$  are with the lepton doublets  $(\nu_i, l_i)$  and the Higgs doublet  $(\phi^+, \phi^0)$ . As the Universe expands and cools, the out-of-equilibrium decays of  $N_1$  (i.e., the lightest  $N_i$ ) into  $l^-\phi^+$  and  $l^+\phi^-$  establish a lepton ( $L$ ) asymmetry. This engenders a baryon ( $B$ ) asymmetry through sphaleron interactions which change  $B + L$  but not  $B - L$ .

Consider now the following extension of the SM. Let  $\tilde{h}, \tilde{h}^c$  be heavy singlet scalar quarks of charge  $Q = \mp 1/3$  and baryon

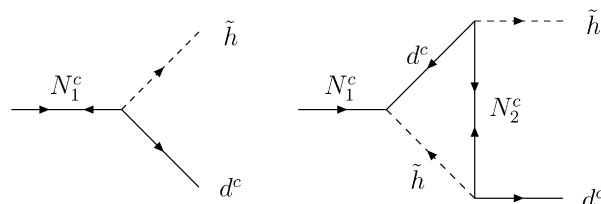


Fig. 1. Tree- and one-loop diagrams for  $N_1^c \rightarrow d^c \tilde{h}$ .

number  $B = \mp 2/3$ ; and let  $N_{1,2}^c$  be heavy singlet neutral fermions of  $B = 1$ . As a result, the new interactions

$$QQ\tilde{h}, \quad u^c d^c \tilde{h}^c, \quad d^c N^c \tilde{h}, \quad (1)$$

where  $Q = (u, d)$ , are allowed. Suppose also that  $N_{1,2}^c$  are Majorana so that baryon number is only multiplicatively conserved. Then the decays

$$N_1^c \rightarrow \bar{d}^c \tilde{h}^* \rightarrow \bar{d}^c du \quad (B = +1), \quad (2)$$

$$N_1^c = \bar{N}_1^c \rightarrow d^c \tilde{h} \rightarrow d^c \bar{d}\bar{u} \quad (B = -1), \quad (3)$$

generate a baryon asymmetry under the same conditions as in leptogenesis. Again  $N_2^c$  is needed to obtain the required CP violation from the interference of the tree- and one-loop diagrams as shown in Fig. 1.

As an illustration, let  $m_{N^c} \sim 10^6$  GeV and  $d^c N_2^c \tilde{h}$  couplings  $\sim 10^{-2}$ , then a decay asymmetry of order  $10^{-6}$  may be established, enabling a baryon asymmetry  $\eta_B \sim 10^{-10}$  to be

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Table 1  
Particle content of  $\underline{27}$  of  $E_6$  under  $SU(3)_C \times SU(2)_L \times U(1)_Y$  and  $U(1)_N$

| Superfield               | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | $U(1)_N$ |
|--------------------------|--|----------|
| $Q = (u, d)$             | $(3, 2, 1/6)$                          | 1        |
| $u^c$                    | $(3^*, 1, -2/3)$                       | 1        |
| $e^c$                    | $(1, 1, 1)$                            | 1        |
| $d^c$                    | $(3^*, 1, 1/3)$                        | 2        |
| $L = (\nu, e)$           | $(1, 2, -1/2)$                         | 2        |
| $h$                      | $(3, 1, -1/3)$                         | -2       |
| $\bar{E} = (E^c, N_E^c)$ | $(1, 2, 1/2)$                          | -2       |
| $h^c$                    | $(3^*, 1, 1/3)$                        | -3       |
| $E = (\nu_E, E)$         | $(1, 2, -1/2)$                         | -3       |
| $S$                      | $(1, 1, 0)$                            | 5        |
| $N^c$                    | $(1, 1, 0)$                            | 0        |

obtained. The out-of-equilibrium condition requires however that the  $d^c N_1^c \tilde{h}$  couplings be less than about  $10^{-5}$ . Sphaleron interactions will modify this pure  $B$  asymmetry into a  $B-L$  asymmetry in exact analogy to what happens to a pure  $L$  asymmetry in the case of leptogenesis.

This new idea of multiplicatively conserved baryon number and baryogenesis turns out to be naturally realized in the context of a supersymmetric string-inspired extension of the SM proposed some time ago [7], with many interesting features in its own right [8,9]. It is based on  $E_6$  with matter content given by three  $\underline{27}$  representations and with gauge interactions of the SM plus those of  $U(1)_N$ , which is a linear combination of  $U(1)_\psi$  and  $U(1)_\chi$  in the decomposition:

$$E_6 \rightarrow SO(10) \times U(1)_\psi, \quad (4)$$

$$SO(10) \rightarrow SU(5) \times U(1)_\chi. \quad (5)$$

In terms of the maximal subgroup  $SU(3)_C \times SU(3)_L \times SU(3)_R$  of  $E_6$ , the  $U(1)_N$  charge is given by

$$Q_N = 6Y_L + T_{3R} - 9Y_R, \quad (6)$$

where  $T_{3L,3R}$  and  $Y_{L,R}$  are the usual quantum numbers of the  $SU(2) \times U(1)$  decompositions of  $SU(3)_{L,R}$ . The particle content of a  $\underline{27}$  multiplet of  $E_6$  is shown in Table 1.

There are eleven possible generic trilinear terms invariant under  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ . Five are necessary for fermion masses, namely

$$Qu^c \bar{E}, \quad Qd^c E, \quad Le^c E, \quad SE \bar{E}, \quad Shh^c, \quad (7)$$

for  $m_u, m_d, m_e, m_E, m_h$  respectively. The other six are

$$LN^c \bar{E}, \quad QLh^c, \quad u^c e^c h, \quad d^c N^c h, \quad QQh, \quad u^c d^c h^c, \quad (8)$$

some of which must be absent to prevent rapid proton decay. Hence all such models require an additional discrete symmetry, the simplest of which is of course a single  $Z_2$ , resulting in eight generic possibilities, as shown already many years ago [10]. I consider here instead an exactly conserved  $(-)^L \times (-)^{3B}$  symmetry as shown in Table 2.

As a result, all terms of Eq. (7) are allowed as well as the following from Eq. (8):

$$QQh, \quad u^c d^c h^c, \quad d^c N^c h, \quad (9)$$

Table 2  
Particle content of  $\underline{27}$  of  $E_6$  under  $(-)^L$  and  $(-)^{3B}$

| Superfield      | $(-)^L$ | $(-)^{3B}$ |
|-----------------|---------|------------|
| $Q, u^c, d^c$   | +       | -          |
| $L, e^c$        | -       | +          |
| $h, h^c$        | +       | +          |
| $E, \bar{E}, S$ | +       | +          |
| $N^c$           | +       | -          |

Table 3  
Division of  $E, \bar{E}, S$  superfields under  $(-)^L$  and  $(-)^{3B}$

| Superfield                        | $(-)^L$ | $(-)^{3B}$ |
|-----------------------------------|---------|------------|
| $E_1, \bar{E}_1, S_1$             | +       | +          |
| $E_{2,3}, \bar{E}_{2,3}, S_{2,3}$ | -       | -          |

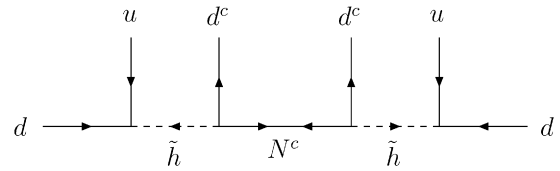


Fig. 2. Diagram for deuteron decay and neutron–antineutron oscillation.

exactly as desired, i.e., those of Eq. (1). In addition,  $N^c$  are allowed large Majorana masses, and the undesirable bilinear terms  $L\bar{E}$  and  $d^c h$  (allowed by  $U(1)_N$  alone) are forbidden by  $(-)^L$  and  $(-)^{3B}$  respectively. Successful baryogenesis is therefore possible. Note that below the  $N^c$  mass scale, the theory is both  $B$  and  $L$  conserving with  $h, h^c$  having  $B = \mp 2/3$ . This is important so that the only violation ( $B + L$ ) comes from the sphalerons.

Since  $(-)^{3B}$  is conserved, the proton is stable, but the deuteron is not, and neutron–antineutron oscillations are allowed. The latter two processes are based on the same mechanism responsible for baryogenesis, i.e., Eqs. (2) and (3), as shown in Fig. 2. As an illustration, let  $m_{N^c} \sim 10^6$  GeV,  $m_{\tilde{h}} \sim 10^3$  GeV,  $d^c N^c \tilde{h}$  couplings  $\sim 10^{-2}$ , and  $ud\tilde{h}$  couplings  $\sim 10^{-5}$ , then  $(10^{-2})^2(10^{-5})^2/(10^6)(10^3)^4 = (10^{-16})^2$ , implying an equivalent scale of  $10^{16}$  GeV in the usual consideration of baryon-number nonconserving processes at the GeV scale, in agreement with all present experimental bounds. As for  $R$  parity, it remains the same, i.e.,  $R = (-)^{3B+L+2j}$ , in this model as in the Minimal Supersymmetric Standard Model (MSSM). The lightest neutralino is thus again a good candidate for the dark matter of the Universe.

Since  $N^c$  is odd under  $(-)^{3B}$  but even under  $(-)^L$ , there is no  $LN^c \bar{E}$  coupling and  $N^c$  does not play the role of a singlet right-handed neutrino as is normally assumed. This means that neutrino masses remain zero, contrary to present data on neutrino oscillations. To remedy this shortcoming, a very interesting variation of the above scenario is described below.

There are three sets of  $E, \bar{E}, S$  superfields, but only one is required to break  $SU(2)_L \times U(1)_Y \times U(1)_N$  and to endow all fermions (except the neutrinos) with masses. Let them thus be divided as in Table 3. In that case, the generic  $SE\bar{E}$  couplings are restricted to  $S_1 E_{1,2,3} \bar{E}_{1,2,3}, S_{2,3} E_1 \bar{E}_{2,3}, S_{2,3} E_{2,3} \bar{E}_1$ , and

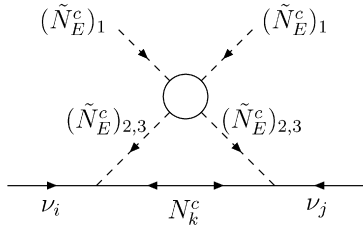


Fig. 3. Two-loop generation of neutrino mass.

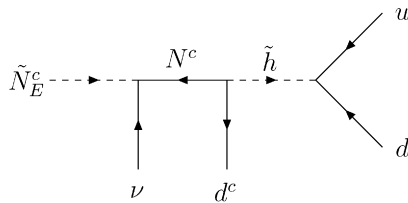


Fig. 4. Diagram for the long-lived decay of  $\tilde{N}_E^c$ .

the important new couplings

$$L_i N_j^c \tilde{E}_{2,3} \quad (10)$$

are allowed. The decays of  $N_1^c$  into  $l^- \tilde{E}^+$  and  $l^+ \tilde{E}^-$  now also generate a lepton asymmetry. Thus remarkably, both  $B$  and  $L$  asymmetries are established in the decays of  $N_1^c$ , and at energies below its mass, the theory conserves both  $B$  and  $L$ . Sphaleron interactions then convert both asymmetries into a  $B-L$  asymmetry, the baryon component of which is observed today.

Using the interactions of Eq. (10) and the one-loop effective  $[(\tilde{N}_E^c)_1^\dagger (\tilde{N}_E^c)_{2,3}]^2$  couplings from supersymmetry breaking, seesaw neutrino masses are now generated in two loops as shown in Fig. 3. This has the same structure discussed in Ref. [9]. However, no extra  $Z_2$  symmetry beyond  $(-)^L$  and  $(-)^{3B}$  is assumed here. For  $N^c$  of order  $10^6$  GeV, realistic neutrino masses of order 0.1 eV may be obtained. This is well below the bound of  $10^9$  GeV on the reheating temperature of the Universe for avoiding the overproduction of gravitinos [11].

Since  $(-)^{3B+L}$  is still the same, i.e., even, for all  $E, \tilde{E}, S$  superfields,  $R$  parity is unchanged in this scenario. However, the lightest particle contained in  $E_{2,3}, \tilde{E}_{2,3}$ , and  $S_{2,3}$  must decay through  $N^c$ , so its lifetime is very long, say of order  $10^3$  seconds. [If it is much bigger than that, this late decaying particle will have an observable contribution to the power spectrum of the cosmic microwave background.] An example of such a decay is shown in Fig. 4. Depending on their masses, there may even be two such long-lived particles, one with  $R$  parity even and the other odd.

To summarize, the new idea of multiplicative conservation of baryon number and baryogenesis has been proposed.

(1) It requires at the minimum the existence of a scalar singlet quark  $\tilde{h}$  of charge  $Q = -1/3$  and baryon number  $B = -2/3$ . If kinematically allowed,  $\tilde{h}\tilde{h}^*$  will be produced at the

Large Hadron Collider (LHC), and identified through their subsequent decays into 4 quark jets with large transverse momenta and large pairwise invariant masses.

(2) The lightest of at least 2 heavy neutral singlet Majorana fermions  $N_i^c$  may then decay into  $\tilde{h}^* \tilde{d}^c$  ( $B = +1$ ) and  $h \tilde{d}^c$  ( $B = -1$ ) and establish a baryon asymmetry of the Universe. The mass of  $N_1^c$  (the lightest  $N_i^c$ ) may be of order  $10^6$  GeV.

(3) The proton is stable, but the deuteron is not, and neutron-antineutron oscillations are allowed.

(4) This scenario is naturally realized in a known supersymmetric string-inspired extension of the SM, i.e.,  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$  with particle content given by three  $\underline{27}$  representations of  $E_6$ .

(5) If kinematically allowed, the  $U(1)_N$  gauge boson  $Z_N$  will be discovered with ease at the LHC because it has both quark and lepton couplings (see Table 1).

(6) Two-loop radiative seesaw neutrino masses are also possible in an interesting variation of the model, where both  $B$  and  $L$  asymmetries are established by the decays of  $N_1^c$ , to be converted into a  $B-L$  asymmetry by sphaleron interactions.

(7) The lightest particle odd under  $R = (-)^{3B+L+2j}$  is a candidate for the dark matter of the Universe as in the MSSM. However, there is now at least one particle which is very long-lived, and will also appear as missing energy at the LHC.

### Acknowledgement

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