CPT-2000/P.4083
UCRHEP-T293
November 2000

arXiv:hep-ph/0011197v1 16 Nov 2000

Allowable Low-Energy E_6 Subgroups from Leptogenesis

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Abstract

There are only two viable low-energy E_6 subgroups: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ or $SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}$, which would not erase any pre-existing lepton asymmetry of the Universe that may have been created by the decay of heavy singlet (right-handed) neutrinos or any other mechanism. They are also the two most favored E_6 subgroups from a recent analysis of present neutral-current data. We study details of the leptogenesis, as well as some salient experimental signatures of the two models.

In the energy range of 100 GeV to 1 TeV, physics beyond the standard model (SM) may appear in two ways. One is the possible addition of supersymmetry; the other is the possible extension of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group to a larger symmetry group G. Both of these options are realized in the E_6 superstring models which predict the existence of new particles, such as an extra gauge boson Z', at $\mathcal{O}(1)$ TeV [1].

As required by the solar and atmospheric neutrino data [2], any extension of the SM should include a mechanism for generating small nonzero neutrino masses. It should also be consistent with the present observed baryon asymmetry of the Universe. If it contains $B-L$ violating interactions at energy scales in the range $10^2 - 10^{12}$ GeV, these together with the $B+L$ violating electroweak sphalerons [3] would erase [4] whatever lepton or baryon asymmetry that may have been created at an earlier epoch of the Universe [5].

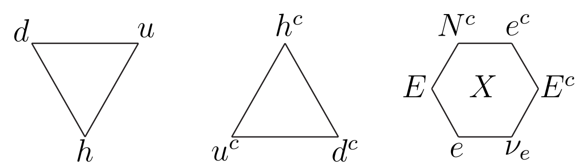
In this Letter we show that if G is a subgroup of E_6, and if G survives down to $\mathcal{O}(1)$ TeV as is expected in these theories, then the constraint of successful leptogenesis [6, 7] from the decay of heavy singlet (right-handed) neutrinos N results *uniquely* in only two possible candidates. One is $G_1 = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ [8], and the other is $G_2 = SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L + Y'_R}$ [9], where $SU(2)'_R$ is not the conventional $SU(2)_R$. Only these groups allow N to have zero quantum numbers with respect to all of their transformations. Any other subgroup of E_6 would result in lepton-number violating interactions at $\mathcal{O}(1)$ TeV as it is broken down to the SM. Remarkably, $G_{1,2}$ happen to be also the two most favored E_6 subgroups from a recent analysis [10] of present neutral-current data. This is a possible hint that one of these two models may in fact be correct.

Whereas there is only one version [9] of the model based on G_2, we find 2 (and only 2) phenomenologically viable versions of G_1, and work out the details of the leptogenesis in all 3 cases. In addition to specific Z' properties at colliders, we also predict the discovery of $W_R^\pm$ in the G_2 model. Among other distinctive experimental signatures are the s-channel diquark resonances at hadron colliders, which can be tested up to the *multi* TeV scale at the LHC [11].

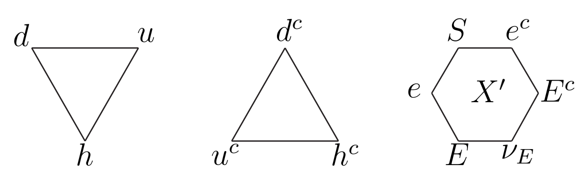
The fundamental $\underline{27}$ representation of E_6 may be classified according to its maximal subgroup $SU(3)_C \times SU(3)_L \times SU(3)_R$. In the notation where all fermions are considered left-handed, one has the particle assignment

$$(u, d, h) \sim (3, 3, 1), \quad (h^c, d^c, u^c) \sim (3^*, 1, 3^*), \tag{1}$$

whereas ν_e, e, e^c together with the new superfields $N^c, \nu_E, E, N_E^c, E^c, S$ are contained in $(1, 3^*, 3)$. Under the decomposition $SU(3)_L \to SU(2)_L \times U(1)_{Y_L}$, $SU(3)_R \to SU(2)_R \times U(1)_{Y_R}$, they may be represented pictorically as



where the horizontal axis measures $T_{3L} + T_{3R}$, the vertical axis $Y_L + Y_R$, and $X = \nu_E, S, N_E^c$. In this particle assignment, the assumption is that the $SU(2)_R$ subgroup contains the quark doublet (d^c, u^c) as in the usual left-right model. However, as was first pointed out in Ref. [9], a different decomposition of $SU(3)_R$ may be chosen, i.e. $SU(2)'_R$, where (h^c, u^c) is the doublet. A third way is to choose the direction of symmetry breaking so that (h^c, d^c) is a doublet [12]. These 3 choices are merely the familiar old T, V, U isospins of $SU(3)$. With the interchange $d^c \leftrightarrow h^c$ in going from $SU(2)_R$ to $SU(2)'_R$, one must also interchange $(\nu_e, e) \leftrightarrow (\nu_E, E)$, and $N^c \leftrightarrow S$. The new pictorial representation is



where $X' = \nu_e, N^c, N_E^c$. The electric charge is given by

$$Q = T_{3L} + Y, \quad Y = Y_L + T_{3R} + Y_R. \tag{2}$$

If $SU(2)_R \times U(1)_{Y_R}$ is replaced by $SU(2)'_R \times U(1)_{Y'_R}$, then

$$T'_{3R} = \frac{1}{2}T_{3R} + \frac{3}{2}Y_R, \quad Y'_R = \frac{1}{2}T_{3R} - \frac{1}{2}Y_R. \tag{3}$$

Hence $T'_{3R} + Y'_R = T_{3R} + Y_R$ so that Y remains the same as it must. As far as the SM is concerned, the two extensions are equally viable and no interaction involving only the SM particles, i.e. $u, d, u^c, d^c, \nu_e, e, e^c$ and the corresponding gauge bosons, can tell them apart.

Another way to extend the SM is to attach an extra $U(1)$. In this case, E_6 offers the choice of a linear combination of two distinct $U(1)$ subgroups [13], i.e. $E_6 \to SO(10) \times U(1)_\psi$ and $SO(10) \to SU(5) \times U(1)_\chi$, with

$$Q_\psi = \sqrt{\frac{3}{2}}(Y_L - Y_R), \quad Q_\chi = \sqrt{\frac{1}{10}}(5T_{3R} - 3Y). \tag{4}$$

Let $Q_\alpha \equiv Q_\psi \cos\alpha + Q_\chi \sin\alpha$, then all possible $U(1)$ extensions of the SM under E_6 may be studied [14] as a function of α.

Let us now discuss the role of $B-L$ in E_6 models. It is well-known that $Y_L + Y_R = (B-L)/2$ as far as the SM particles are concerned [15]. For the new fermions belonging to the E_6 fundamental representation, this may be extended as a definition because their Yukawa interactions with the SM particles must be invariant under G. With this assignment, all Yukawa and gauge interactions *conserve* $B-L$. Among the five neutral fermions in E_6, only two (ν_e and N^c) carry nonzero $B-L$ quantum numbers (-1 and 1). Hence the *only* useful source of $B-L$ violation in any E_6 model is the large Majorana mass of N^c, which is of course also the reason why neutrino masses are small (from the seesaw mechanism) to begin with.

In a successful scenario of leptogenesis [6], the decay of the *physical* heavy Majorana neutrino N (i.e. N^c plus its conjugate) must satisfy the out-of-equilibrium condition

$$\Gamma_N < H(T = m_N) = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{T^2}{M_P}, \tag{5}$$

where Γ_N is its decay width, $H(T)$ the Hubble expansion rate and g_* the effective number of massless degrees of freedom at the temperature T. This requires m_N to be many orders of magnitude greater than 1 TeV, so N^c cannot transform under the low-energy gauge group G. Since $N^c \sim (1; 0; -1/2; 1/2)$ under $SU(3)_C \times T_{3L} \times T_{3R} \times (Y_L + Y_R)$, this group (i.e. the conventional left-right model) is forbidden by leptogenesis. On the other hand, $N^c \sim (1; 0; 0; 0)$ under $SU(3)_C \times T_{3L} \times T'_{3R} \times (Y_L + Y'_R)$, hence the skew left-right model [9] is allowed. In the $U(1)_\alpha$ models, N^c transforms trivially only if $\tan\alpha = \sqrt{1/15}$. This is called $U(1)_N$ [8] with

$$Q_N = \sqrt{\frac{1}{40}}(6Y_L + T_{3R} - 9Y_R), \tag{6}$$

and is indeed zero for N^c, i.e. $Y_L = 1/3$, $T_{3R} = -1/2$, and $Y_R = 1/6$.

Thus the only possible E_6 subgroups allowed by leptogenesis are those given by the skew $SU(2)'_R$ and $U(1)_N$ models. While details of the leptogenesis and the low-energy phenomenology are different in these two models, their choice follows from a *single* and *unique* group-theoretical argument which has nothing to do with model building. Indeed, if not for the fact that $\sin^2\theta_W \neq 3/8$ at low energies, the breaking of $SU(2)'_R \times U(1)_{Y_L+Y'_R}$ would result in $U(1)_N \times U(1)_Y$.

There are many virtues [8, 16] associated with these two models. They are also the most favored [10] of all known gauge extensions of the SM, based on present neutral-current data from atomic parity violation [17] and precision measurements of the Z width. The $U(1)_N$ model was not considered in Ref.[10], but it can easily be included in their Fig. 1 by noting that it has $\alpha = 0$ and $\tan\beta = \sqrt{15}$ in their notation, thus placing it within the 1σ contour together with the $SU(2)'_R$ model.

We shall now work out details of the leptogenesis in these models. The most general superpotential for the $U(1)_N$ model coming from the $\underline{27} \times \underline{27} \times \underline{27}$ decomposition of the E_6

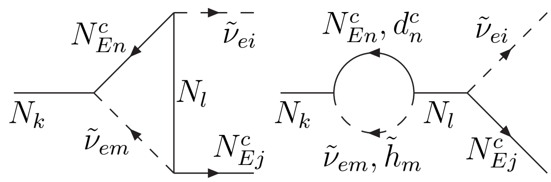


Figure 1: Loop diagrams interfering with the N_k tree decay.

fundamental representation is

$$\begin{aligned} W = & \lambda_1^{ijk} u_i^c Q_j H_k^c + \lambda_2^{ijk} d_i^c Q_j H_k + \lambda_3^{ijk} e_i^c L_j H_k + \\ & \lambda_4^{ijk} S_i H_j H_k^c + \lambda_5^{ijk} S_i h_j h_k^c + \lambda_6^{ijk} e_i^c h_j u_k^c + \lambda_7^{ijk} h_i^c Q_j L_k + \\ & \lambda_8^{ijk} d_i^c h_j N_k^c + \lambda_9^{ijk} h_i Q_j Q_k + \lambda_{10}^{ijk} u_i^c d_j^c h_k^c + \lambda_{11}^{ijk} L_i H_j^c N_k^c, \end{aligned} \tag{7}$$

where we denote (ν_E, E) as H and (E^c, N_E^c) as H^c. The terms λ_{1-5} give masses to all fermions and must be present in any model. $SU(2)_L \times U(1)_Y$ is broken by $\langle \tilde{N}_E^c \rangle$ and $\langle \tilde{\nu}_E \rangle$, while $\langle \tilde{S} \rangle$ breaks $U(1)_N$ [as well as $SU(2)'_R \times U(1)_{Y_L + Y'_R}$] and gives masses of order $M_{Z'}$ to E, h, ν_E, and N_E^c. Whereas W conserves $B - L$ automatically, there are some terms which violate $B + L$. To prevent rapid proton decay, an appropriate Z_2 symmetry (extension of R-parity) must be imposed. There are 8 ways to do that, resulting in 8 different models [18]. However, the requirements of leptogenesis and nonzero neutrino masses single out only 2 allowed possibilities. If (L, e^c), N^c and (h, h^c) are all odd under Z_2, then $\lambda_{9,10} = 0$ in Eq. (7) which is called Model 1. Here N^c is a lepton ($L = -1$) and h is a leptoquark ($B = 1/3$, $L = 1$). If (h, h^c) is even and the others remain odd, then we get Model 2 with $\lambda_{6,7,8} = 0$ and h is now a diquark ($B = -2/3$). Note that leptogenesis is also possible in Model 7 of Ref.[18] with $\lambda_{6-10} = 0$, but as h is stable in this case, it is ruled out by cosmological considerations. Baryogenesis is also allowed in Model 5 of Ref.[18] with $\lambda_{6,7,11} = 0$, but since N^c is now a baryon with $B = 1$ and $L = 0$, neutrinos are exactly massless in that model.

The superpotential of the skew $SU(2)'_R$ model is completely fixed and can be obtained from Eq. (7) by setting $\lambda_4 = \lambda_3$, $\lambda_6 = -\lambda_5$, $\lambda_7 = -\lambda_1$ and $\lambda_{9,10} = 0$. Here h is a leptoquark as in the $U(1)_N$ Model 1. However, the $SU(2)'_R$ decomposition also implies that W_R^- has $L = 1$ and is *odd* under R-parity rather than even. Indeed, W_R^- has $T'_{3R} = -1$ and $Y'_R = 0$, but because of Eq. (3), it has $Y_R = -1/2$.

In general, the heavy Majorana neutrino N_k decays to the $B - L = -1$ final states $\nu_{e_i}\tilde{N}^c_{Ej}$, $\tilde{\nu}_{e_i}N^c_{Ej}$, $e_i\tilde{E}^c_j$, $\tilde{e}_iE^c_j$ and $d^c_i\tilde{h}_j$, $\tilde{d}^c_ih_j$ via the interaction terms λ_{11} and λ_8 in Eq. (7), respectively, and to their conjugate states with $B - L = 1$. To establish a $B - L$ asymmetry, one needs: (*i*) $B - L$ violation, from the N Majorana mass; (*ii*) CP violation, from the complex couplings $\lambda_{8,11}$; and (*iii*) the out-of-equilibrium condition of Eq. (5). An equal asymmetry is also generated from the corresponding decays of the scalar partners $\tilde{N}_k$ [7]. The subsequent decays of N^c_{Ej}, E^c_j and h_j or their superpartners to SM particles do not affect the asymmetry because they conserve $B - L$.

Technically, the $B - L$ asymmetry ε_k is generated from the interference between tree-level N_k decays and one-loop diagrams, some of which are depicted in Fig.1 for one particular final state. Thus $\varepsilon_k = \varepsilon_k^V + \varepsilon_k^S$, where ε_k^V and ε_k^S are vertex and self-energy contributions respectively. They are given by

$$\begin{aligned} \varepsilon_V^k &= -\frac{1}{8\pi}\sum_{l,m,n}\frac{\sum_{a;i,j} C_a \mathrm{Im}[\lambda_a^{ijk*}\lambda_a^{mnk*}\lambda_a^{mjl}\lambda_a^{inl}]}{\sum_{a;ij} C_a|\lambda_a^{ijk}|^2} \\ &\quad \sqrt{x_l}\Big[(1+x_l)\mathrm{Log}(1+1/x_l) - 1\Big], \qquad (8) \\ \varepsilon_S^k &= -\frac{1}{4\pi}\sum_{l,m,n}\frac{\sum_{a,b;i,j} C_{a,b} \mathrm{Im}[\lambda_a^{ijk*}\lambda_b^{mnk*}\lambda_b^{mnl}\lambda_a^{ijl}]}{\sum_{a;ij} C_a|\lambda_a^{ijk}|^2} \\ &\quad \sqrt{x_l}(x_l^2 - 1)^{-1}, \qquad (9) \end{aligned}$$

where $x_l = (m_{N_l}/m_{N_k})^2$, indices $a, b = 8, 11$ denote the interactions of Eq. (7), and the constants $C_8 = 1$, $C_{11} = 2$, $C_{8,8} = 1/2$, $C_{11,11} = 2$, $C_{8,11} = C_{11,8} = 1$ come from the number of diagrams in each case.

Notice two differences from the standard Fukugita-Yanagida mechanism [6]: (*i*) The structures of the flavor indices in ε_k^V and ε_k^S are not the same unless there is only one generation of scalars. (*ii*) There are more self-energy diagrams because the particles in the loop need not be related to those in the final state. This is reflected in Eq. (9) by terms which mix the λ_8 and λ_{11} couplings. Together, (*i*) and (*ii*) imply that in contrast to the models of Refs. [6, 7, 19], the vertex and self-energy contributions to ε_k are *not* related to each other, allowing one or the other to be dominant independently of the values of the N_k masses. This is true even in the $U(1)_N$ Model 2 in which $\lambda_8 = 0$. Also, in the $U(1)_N$ Model 1 and the $SU(2)'_R$ model, the ordinary neutrino masses (induced by $\lambda_{11} L H^c N^c$) need not be related to the lepton asymmetry.

The total decay width of N_k is given by

$$\Gamma_{N_k} = \frac{1}{4\pi} \sum_{i,j} \left(|\lambda_8^{ijk}|^2 + 2|\lambda_{11}^{ijk}|^2 \right) m_{N_k}. \tag{10}$$

Taking $g_* \sim 10^2$, the out-of-equilibrium condition (5) implies $\sum_{i,j}(|\lambda_8^{ijk}|^2 + 2|\lambda_{11}^{ijk}|^2) \lesssim 2 \times 10^{-17}$ GeV^{-1} m_{N_k}. For $m_{N_k} \sim 10^{15}$ GeV, this gives for example $\lambda_8^{ijk}, \lambda_{11}^{ijk} \lesssim 10^{-1}$. As long as Eq. (5) is satisfied, there are no damping effects due to the inverse decay or scattering processes which may affect the $B-L$ asymmetry. The baryon-to-entropy ratio generated by the decays of N_k and $\tilde{N}_k$ is then $n_B/s \sim 2\varepsilon_k n_\gamma/(2s) = (\varepsilon_k/g_*)(45/\pi^4)$ where n_γ is the photon number density per comoving volume. In order to satisfy the observed value $n_B/s \sim 10^{-10}$, we need $\lambda_{8,11}^{ijk}$ typically of order $\sim 10^{-3}$ assuming a maximal CP-violating phase. The out-of-equilibrium condition can therefore be satisfied easily and the asymmetry is produced with the right order of magnitude.

Above the electroweak phase transition, rapid $B+L$ violating sphaleron processes convert the created $B-L$ asymmetry to the observed asymmetry of quarks and leptons. Since the new particle masses are $\mathcal{O}(1)$ TeV, they do not take part in the sphaleron-induced processes. (Although the anomaly is independent of the masses of the new particles, their participation in the sphaleron processes is forbidden by the phase space available at the time of the electroweak phase transition). Thus B and L violations in the sphaleron environment remain approximately the same as in the SM [20]. This completes the successful baryogenesis in our models.

There are some unique experimental signatures of the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ and $SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}$ models. First, the Z' couplings are given by Q_N in the former, and by [21]

$$\frac{-1}{\sqrt{1-2s_w^2}}\left[s_w^2 Y_L + \left(\frac{3s_w^2-1}{2}\right)T_{3R} - \left(\frac{3-5s_w^2}{2}\right)Y_R\right],$$

in the latter. Here $s_w^2 \equiv \sin^2\theta_W$, assuming $g_L = g_R$. For $s_w^2 = 3/8$, this would be proportional to Q_N, reflecting the same group-theoretical origin of these models.

In either model, one linear combination of the three S fermions (call it S_3) becomes massive by combining with the (neutral) gaugino from $U(1)_N$ or $SU(2)'_R$ breaking, resulting in $m_{S_3} \simeq M_{Z'}$, with $M_{Z'}/M_Z \simeq (25s_w^2/6)(u^2/v^2) = 0.96(u^2/v^2)$ in the former [22], and $M_{Z'}/M_Z \simeq [(1-s_w^2)^2/(1-2s_w^2)](u^2/v^2) = 1.10(u^2/v^2)$ in the latter [21], where $u = \langle \tilde{S}_3 \rangle$. The other two S fermions are presumably light and could be considered "sterile" neutrinos [8, 16]. Hence the invisible width of Z' is predicted to have the property

$$\Gamma(Z' \to \nu\bar{\nu} + S\bar{S}) = \left(\frac{62}{15}\right)\Gamma(Z' \to l^- l^+), \tag{11}$$

in the $U(1)_N$ model, and

$$\Gamma(Z' \to \nu\bar{\nu} + S\bar{S}) = \left(\frac{5-16s_w^2+14s_w^4}{6-30s_w^2+39s_w^4}\right)\Gamma(Z' \to l^- l^+),$$

in the skew left-right model.

In addition to the extra neutral gauge boson Z', there is also the charged gauge boson $W_R^\pm$ in the skew left-right model. It has the unusual property that it carries nonzero $B-L$ as explained before. The mass of W_R is given by

$$M_{W_R} \simeq \left(\frac{\cos 2\theta_W}{\cos\theta_W}\right) M_{Z'} = 0.84\ M_{Z'}. \tag{12}$$

It is predicted to decay only into 2 out of the 3 charged leptons because S_3 is heavy and its partner in the $SU(2)'_R$ doublet is necessarily a mass eigenstate, i.e. e^c, μ^c, or τ^c. If, for example, it is τ^c, then W_R^+ may decay only into e^+S or μ^+S, but not to τ^+S.

The Yukawa interactions differ in the $U(1)_N$ Models 1 and 2, and in the skew $SU(2)'_R$ model, as explained before. Perhaps the most distinctive experimental signatures in this sector are the s-channel diquark h resonances at hadron colliders predicted in the $U(1)_N$ Model 2. At the LHC, the initial state from 2 valence quarks carries $B = 2/3$, hence a diquark resonance may occur without suppression. This allows us to test the existence of the diquark h above 5 TeV [11].

In conclusion, in the context of E_6 superstring theory, the requirement of successful leptogenesis uniquely leads to only two possible extensions of the SM at the TeV energy scale: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N$ and $SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}$. Two Yukawa structures are possible in the former model, but only one in the latter. There are more sources of leptogenesis in these models than in the standard Fukugita-Yanagida scenario, while the smallness of Majorana neutrino masses is assured by the standard seesaw mechanism. They are also the only two such extensions of the SM which are within the 1σ contour of present neutral-current data. This fact allows for the exciting possibility of discovering the extra Z' boson with the predicted couplings in either model, the unusual $W_R^\pm$ boson in the skew left-right model, and the diquark resonances in the $U(1)_N$ Model 2.

This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837. T.H. and U.S. acknowledge the Physics Department, University of California at Riverside for hospitality.

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