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Revelations of the $E_6/U(1)_N$ Model: Two-Loop Neutrino Mass and Dark Matter

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Abstract

The $E_6/U(1)_N$ gauge extension of the Supersymmetric Standard Model, first proposed by Ma, is shown to have exactly the requisite ingredients to realize the important new idea that dark matter is the origin of neutrino mass. With the implementation of a discrete $Z_2 \times Z_2$ symmetry, and particle content given by three $\underline{27}$ representations of E_6, neutrino masses are naturally generated in two loops, with candidates of dark matter in the loops. All particles of this model are expected to be at or below the TeV scale, allowing them to be observable at the LHC.

The $E_6/U(1)_N$ model was proposed in 1995 by one of us [1]. It is a supersymmetric model with matter content given by three $\underline{27}$ representations of E_6, and gauge interactions of the Standard Model plus those of $U(1)_N$, which is a linear combination of $U(1)_\psi$ and $U(1)_\chi$ in the decomposition:

$$E_6 \rightarrow SO(10) \times U(1)_\psi, \tag{1}$$

$$SO(10) \rightarrow SU(5) \times U(1)_\chi. \tag{2}$$

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 [1]

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

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 tabulated below.

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

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

$$Qu^c\bar{E}, \quad Qd^cE, \quad Le^cE, \quad SE\bar{E}, \quad Shh^c, \tag{4}$$

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

$$LN^c\bar{E}, \quad QLh^c, \quad u^ce^ch, \quad d^cN^ch, \quad QQh, \quad u^cd^ch^c, \tag{5}$$

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 [2]. We consider here instead an exactly conserved $Z_2 \times Z_2$ symmetry as tabulated below.

Table 2: Particle content of $\underline{27}$ of E_6 under M parity and N parity.

Superfield	M	N
Q, u^c, d^c	$+$	$+$
L, e^c	$-$	$+$
h, h^c	$-$	$+$
$E_1, \bar{E}_1, S_1$	$+$	$+$
$E_{2,3}, \bar{E}_{2,3}, S_{2,3}$	$+$	$-$
N^c	$-$	$-$

The resulting allowed terms corresponding to Eq. (4) are

$$Qu^c\bar{E}_1, \quad Qd^cE_1, \quad Le^cE_1, \quad S_1hh^c, \quad S_1E_1\bar{E}_1, \quad S_1E_{2,3}\bar{E}_{2,3}, \quad S_{2,3}E_1\bar{E}_{2,3}, \quad S_{2,3}E_{2,3}\bar{E}_1, \tag{6}$$

whereas those of Eq. (5) consist of

$$LN^c\bar{E}_{2,3}, \quad QLh^c, \quad u^ce^ch. \tag{7}$$

The terms d^cN^ch, QQh, and $u^cd^ch^c$ are not allowed. As a consequence, baryon number B and lepton number L are conserved, with $B = 1/3$ and $L = 1$ for h. Proton decay is thus forbidden by exactly conserved M parity.

Consider now the role of N parity. Without it, all three copies of E, $\bar{E}$, and S are Higgs superfields, and N^c are the usual singlet neutrinos, with Dirac masses coming from the $LN^c\bar{E}$ terms. Furthermore, since N^c is trivial under $U(1)_N$, it is allowed to have a very large Majorana mass [1, 3] as in the Standard Model. Thus the observed neutrino masses are Majorana and naturally small by virtue of the canonical seesaw mechanism. This model is very interesting in its own right, and has been explored in some detail [4, 5, 6].

With exactly conserved N parity, there are two important new interrelated consequences. (I) Since $\bar{E}_{2,3}$ do not have vacuum expectation values (otherwise N parity would be broken), there are no Dirac masses linking ν with N^c. Hence neutrinos are massless at tree level in this model. (II) The lightest particle odd under N is absolutely stable and may be considered a candidate for the dark matter of the Universe [7]. It may also interact with ν and N^c to induce a Majorana mass for ν in a one-loop radiative version of the seesaw mechanism, as first proposed by one of us [8]. Variants of this basic idea have also been discussed [9, 10, 11, 12, 13, 14].

The idea that the Standard Model may be extended to include a second *dark* scalar doublet $\Phi_2 = [H^\pm, (H^0 + iA^0)/\sqrt{2}]$ (which is odd under some new unbroken Z_2 symmetry) was considered many years ago [15, 16]. Either H^0 or A^0 is then absolutely stable, and presumably an acceptable candidate for dark matter. This simple observation lay dormant for almost thirty years until recently when it was revived in Ref. [8]; then it was studied seriously for the first time in Ref. [17] and is now receiving much wider attention [11, 18, 19, 20, 21, 22].

First it should be pointed out that H^0 and A^0 cannot be degenerate in mass, otherwise they interact with the Z boson in the same way as a scalar neutrino in supersymmetry, and it has been established for a long time that the latter cannot be the sole source of dark matter because its elastic scattering cross section with nuclei is too big to satisfy present constraints from direct search experiments [7]. In the Standard Model, the mass splitting of H^0 and A^0 comes from the term

$$\frac{1}{2}\lambda_5(\Phi_1^\dagger \Phi_2)^2 + H.c. \tag{8}$$

which is also necessary for inducing a Majorana neutrino mass in one loop, as explained in Ref. [8]. This quartic scalar term is not allowed in supersymmetry, but may be obtained in one loop as the supersymmetry is broken softly, as shown below.

Using Eq. (8) and the notation $\Phi_1 = (\phi^+, \phi^0)$, $\Phi_2 = (\eta^+, \eta^0)$, it was shown in Ref. [8] that a radiative Majorana neutrino mass is obtained in one loop, as shown in Fig. 1.

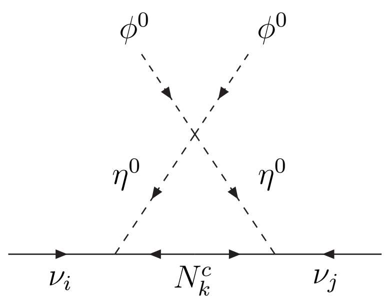

Figure 1: Would-be one-loop generation of neutrino mass.

Let $\eta^0 = (H^0 + iA^0)/\sqrt{2}$, $\langle \phi^0 \rangle = v$, $m_0 = m(H^0)$, $m_A = m(A^0)$, $m_k = m(N_k^c)$, and assuming that $m_A^2 - m_0^2 = -2\lambda_5 v^2$ is much smaller in magnitude than m_0^2, the radiative neutrino mass matrix is given by [8]

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{f_{ik} f_{jk} m_k}{m_k^2 - m_0^2} \left[1 - \frac{m_k^2}{m_k^2 - m_0^2} \ln \frac{m_k^2}{m_0^2} \right], \tag{9}$$

where f_{ik} are the $\nu_i N_k^c \eta^0$ Yukawa couplings.

In the $E_6/U(1)_N$ model, $\lambda_5 = 0$ because of supersymmetry. As the latter is softly broken, an effective nonzero λ_5 for the quartic scalar coupling $[(\tilde{N}_E^c)_1^\dagger (\tilde{N}_E^c)_{2,3}]^2$ may be obtained at tree level [12], but here it appears only in one loop, as shown in Fig. 2 and Fig. 3.

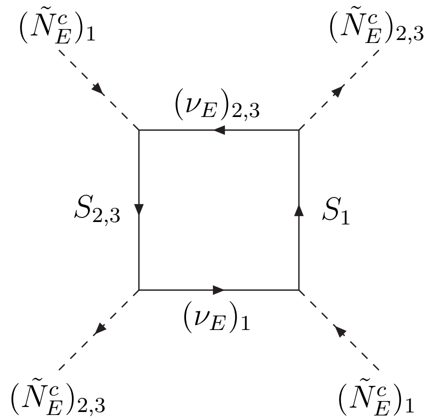

Figure 2: One of four diagrams contributing to λ_5 from a fermion loop.

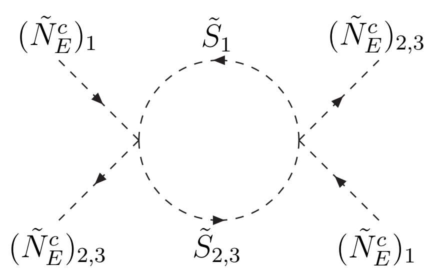

Figure 3: One of eight diagrams contributing to λ_5 from a scalar loop.

In unbroken supersymmetry, the sum of all these diagrams is exactly zero. As the supersymmetry is broken, an effective nonzero λ_5 will be obtained, and since it comes from one loop, the resulting Majorana neutrino mass is a two-loop effect. This allows for the possibility of a much lower mass scale for N^c and all the other particles appearing in the loop. This scenario is thus potentially verifiable at the LHC (Large Hadron Collider).

The existence of M parity implies the exact conservation of the usual R parity of the MSSM (Minimal Supersymmetric Standard Model), i.e. quarks and leptons have even R, their scalar partners have odd R, whereas the scalar particles corresponding to E, $\bar{E}$, and S have even R, their fermionic partners have odd R. The neutralino sector is now a 6×6 mass matrix spanning the gauginos of $U(1)_N$, $U(1)_Y$, and the third component of $SU(2)_L$, as well as the Higgsinos $(\nu_E)_1$, $(N_E^c)_1$, and S_1. Details have already been given in Ref. [4]. Without N parity, the lightest mass eigenstate of this sector is the sole candidate for the dark matter of the Universe, but the situation here is more complicated.

The existence of N parity requires at least one more particle which is absolutely stable. Consider the two classes of particles: $(R,N) = (+,-)$ and $(R,N) = (-,-)$. Take the lightest one from each and consider their interaction with the lightest particle of the class $(R,N) = (-,+)$. Two of the three must then be stable and they may or may not include the one associated with the MSSM. If no particle has a mass greater than the sum of the other two, then all three are dark-matter candidates, as pointed out already in Ref. [12].

The three N^c fermions have $(R,N) = (+,-)$ and their scalar partners have $(R,N) = (-,-)$. The six $(\nu_E)_{2,3}$, $(N_E^c)_{2,3}$, and $S_{2,3}$ fermions have $(R,N) = (-,-)$ and their scalar partners have $(R,N) = (+,-)$. In general, we expect all their masses to be of order the supersymmetry breaking scale. However, there is one exception. Consider the 6×6 mass matrix spanning $(\nu_E)_{2,3}$, $(N_E^c)_{2,3}$, and $S_{2,3}$. It is of the form

$$\mathcal{M} = \begin{pmatrix} 0 & A & B \\ A & 0 & C \\ B & C & 0 \end{pmatrix}, \tag{10}$$

where each entry is a 2×2 matrix. Now A comes from $\langle \tilde{S}_1 \rangle$, B from $\langle (\tilde{N}_E^c)_1 \rangle$, and C from $\langle (\tilde{\nu}_E)_1 \rangle$. Since $\langle \tilde{S}_1 \rangle$ breaks $U(1)_N$, it is expected to be an order of magnitude greater than the others which break $SU(2)_L \times U(1)_Y$. Hence the lightest particle in this sector is likely to be mostly $S_{2,3}$ with a mass of order $|2BC/A|$ which could be much less than 100 GeV.

The $E_6/U(1)_N$ model is defined as the linear combination of $U(1)_\psi$ and $U(1)_\chi$ in Eqs. (1) and (2), under which N^c is trivial. As a result, the unwelcomed bilinear terms hd^c and $L\bar{E}$

are admitted as well. However the former is forbidden by M parity and the latter by N parity. At the TeV energy scale, this model predicts a new Z_N gauge boson, leptoquark scalars $\tilde{h}$ which decay into ue and $d\nu$, singlet neutral fermions N^c which decay into leptons plus dark-matter scalars, etc. A rich tapestry of particles and their interactions awaits at the LHC.

Other variants of this model are easily perceived. For example, if h, h^c are even under M parity, then QLh^c and $u^c e^c h$ are forbidden, but QQh and $u^c d^c h^c$ are allowed, so that $\tilde{h}^c$ become diquark scalars which decay into ud. As for neutrino masses, the crucial term is $LN^c\bar{E}_{2,3}$ of Eq. (7). This means that even with one N^c, two nonzero masses may be obtained, which is sufficient to account for present neutrino-oscillation data. The other two N^c could then be chosen to have very small couplings so that their decay into leptons and antileptons would be out of thermal equilibrium and would generate a lepton asymmetry, which gets converted during the electroweak transition by sphalerons into the observed baryon asymmetry of the Universe. Details will be presented elsewhere.

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