Neutrino Exotica in the Skew E$_6$ Left-Right Model

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Abstract

With the particle content of the 27 representation of E$_6$, a skew left-right supersymmetric gauge model was proposed many years ago, with a variety of interesting phenomenological implications. The neutrino sector of this model offers a natural framework for obtaining small Majorana masses for $\nu_e$, $\nu_\mu$, and $\nu_\tau$, with the added bonus of accommodating 2 light sterile neutrinos.
With the advent of superstring theory\cite{1}, it was recognized early on\cite{2} that the gauge symmetry $E_6$ may be relevant for discussing low-energy particle physics phenomenology\cite{3}. There are two ideas: (1) the particle content of the Minimal Supersymmetric Standard Model (MSSM) may be extended to include all particles contained in the fundamental 27 representation of $E_6$; and (2) the standard-model gauge group may be extended as well. The most actively pursued such approach\cite{4, 5} is to add an extra U(1).

A very different and unique alternative was proposed many years ago\cite{6}, which considers instead an unconventional $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$ decomposition of the 27 representation of $E_6$, resulting in a variety of interesting phenomenological implications. Among these are the natural absence of flavor-changing neutral currents at tree level\cite{8} despite the presence of $SU(2)_R$, the possibility of breaking $SU(2)_R$ at or below the TeV scale with only Higgs doublets and bidoublets\cite{7} without conflicting with present phenomenology, and the appearance of an effective two-doublet Higgs sector different\cite{8} from that of the MSSM, with the interesting (and currently very relevant) property that the tree-level upper bound of the lightest neutral Higgs-boson mass is raised from $M_Z$ in the MSSM to $\sqrt{2}M_W$ in this case.

Two possible deviations from the standard model have recently been observed. One is a new determination of the weak charge of atomic cesium\cite{9}. The other is a new analysis of the hadronic peak cross section at the $Z$ resonance\cite{10}. Based on these data, it has now been shown\cite{11} that the model of Ref.\cite{6} is in fact the most favored of all known gauge extensions of the standard model.

This paper deals with another aspect of this remarkable model, i.e. that of its neutrinos. In the original proposal\cite{6}, neutrino masses were assumed to be zero for simplicity. [Recall that in 1986, neutrino oscillations were not clearly established.] However, such is not an essential feature of this model. It is in fact more natural that $\nu_e$, $\nu_\mu$, and $\nu_\tau$ acquire small
Majorana masses through the usual seesaw mechanism, and that 2 light sterile neutrinos are accommodated in this model, resulting in a number of exotic phenomena which may be tested in future experiments.

The skew $E_6$ left-right model is based on the observation that there are two ways of identifying the standard-model content of the $27$ representation of $E_6$. Written in its $[SO(10), SU(5)]$ decomposition, we have

$$27 = (16, 5^*) + (16, 10) + (16, 1) + (10, 5^*) + (10, 5) + (1, 1).$$

(1)

The usual assumption is that the standard-model particles are contained in the $(16, 5^*)$ and $(16, 10)$ multiplets. On the other hand, if we switch $(16, 5^*)$ with $(10, 5^*)$ and $(16, 1)$ with $(1, 1)$, the standard model remains the same. The difference between the 2 options only appears if the gauge group is extended. In particular, a very different and unique model emerges if the gauge group becomes $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$. In this scenario, the particle assignments are as follows.

$$\begin{align*}
(u, d)_L &\sim (3, 2, 1, 1/6), \quad d^c_L \sim (3^*, 1, 1, 1/3), \\
(h^c, u^c)_L &\sim (3^*, 1, 2, -1/6), \quad h_L \sim (3, 1, 1, -1/3), \\
\begin{pmatrix}
\nu \\
e \\
\psi^0
\end{pmatrix}_L &\sim (1, 2, 2, 0), \quad (e^c, S)_L \sim (1, 1, 2, 1/2), \\
(\xi^0, E)_L &\sim (1, 2, 1, -1/2), \quad N_L \sim (1, 1, 1, 0),
\end{align*}$$

(2)–(5)

where the convention is that all fields are considered left-handed.

The notion of $R$ parity is an important ingredient of this construction. The usual quarks and leptons, i.e. $u, d, u^c, d^c, \nu, e,$ and $e^c$, with the addition of $N$, have $R = +1$ and their scalar supersymmetric partners have $R = -1$ as in the MSSM. The other fermions, i.e. $h, h^c, E, E^c, \psi^0, \xi^0,$ and $S$ have $R = -1$ and their scalar supersymmetric partners have $R = +1$. 

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Furthermore, all gauge bosons have $R = +1$ and gauge fermions have $R = -1$, except $W^\pm_R$ which has $R = -1$ and $\tilde{W}^\pm_R$ which has $R = +1$. This unusual feature is the origin of many desirable and interesting properties\[^3\] of this model which sets it apart from all other gauge extensions of the standard model.

Consider the $R = +1$ neutral fermion sector, i.e. the usual neutrinos $\nu_e, \nu_\mu, \nu_\tau$, and the 3 $N$’s. They are linked by the Yukawa terms $\nu_i N_j \tilde{\psi}^0_k$, where one linear combination of $\tilde{\psi}^0_k$ may be identified with the usual Higgs scalar $h_0^2$ which acquires the vacuum expectation value $v_2$. Furthermore, since $N_j$ transforms trivially under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$, it is allowed to have a nonzero Majorana mass which is presumably large\[^13\]. [In $U(1)$ extensions of the MSSM within the context of $E_6$, the requirement that $N$ transform trivially under $SU(3)_C \times SU(2)_L \times U(1)\Y \times U(1)\y$ uniquely determines it\[^14\] to be a particular linear combination\[^3\] of $U(1)\psi$ and $U(1)\chi$ with mixing angle $\alpha = -\tan^{-1}\sqrt{1/15}$, where $Q_\alpha = Q_\psi \cos \alpha - Q_\chi \sin \alpha$. This is referred to as $U(1)_N$ or $U(1)_\nu$\[^15\]. However, with two $U(1)$ gauge factors, kinetic mixing\[^16\] must be considered, a complication which is absent in a left-right model.] The resulting $6 \times 6$ neutrino mass matrix is

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m^T_D & m_N \end{pmatrix},$$

where $m_D$ and $m_N$ are themselves $3 \times 3$ matrices. Thus the usual neutrinos acquire small Majorana masses through the canonical seesaw mechanism\[^12\] without any problem. In other gauge extensions, this mechanism is often not available\[^11\].

The $SU(2)_R \times U(1)$ of this model breaks down to the standard-model $U(1)\y$ through the vacuum expectation value $v_3$ of a linear combination of the $\tilde{S}$’s. Let us define that to be $\tilde{S}_3$. Because of the allowed Yukawa terms linking $hh^c, EE^c$, and $\xi^0\psi^0$ to $\tilde{S}_3$, these exotic fermions have masses proportional to $v_3$. However, only 1 of the 3 $S$’s gets a mass at this stage, i.e. $S_3$, as it is linked to a particular linear combination of the two neutral gauge fermions corresponding to $SU(2)_R$ and $U(1)$ through $\tilde{S}_3$. 

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Electroweak symmetry breaking proceeds as in the MSSM, with $\tilde{\xi}_3$ identified as $h_1^0$ and $\tilde{\psi}_3$ as $h_2^0$, having vacuum expectation values $v_1$ and $v_2$ respectively. Now $S_{1,2}$ are no longer massless and if they are light, they could well be called sterile neutrinos\[17\].

Consider now the $R = -1$ neutral fermion sector, i.e. $\xi^0_i$, $\psi^0_i$, $S_i$, and the 3 gauge fermions $\tilde{W}^0_L$, $\tilde{W}^0_R$, and $\tilde{B}$ corresponding to $SU(2)_L$, $SU(2)_R$, and $U(1)$ respectively. They are linked by the

$$f_{ijk}(\xi^0_i e_j c_k - E_i \nu_j c_k - \xi^0_i \psi^0_j S_k + E_i E_j c_S)$$

(7)

terms of the superpotential as well as the gauge interaction terms together with the soft supersymmetry-breaking Majorana mass terms $m_L$, $m_R$, $m_B$ of the gauge fermions. The resulting $12 \times 12$ mass matrix is

$$M = \begin{pmatrix}
0 & -m_{EE} & -f_{i3j}v_2 & m_1 \\
-m_{EE}^T & 0 & -m_{ee} & m_2 \\
-f_{i3j} v_2 & -m_{ee}^T & 0 & m_3 \\
m_1^T & m_2^T & m_3^T & \bar{m}
\end{pmatrix},$$

(8)

where

$$m_1 = \frac{v_1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_L & 0 & -g_B \end{pmatrix}, \quad m_2 = \frac{v_2}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -g_L & g_R & 0 \end{pmatrix},$$

$$m_3 = \frac{v_3}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -g_R & g_B \end{pmatrix}, \quad \bar{m} = \begin{pmatrix} m_L & 0 & 0 \\ 0 & m_R & 0 \\ 0 & 0 & m_B \end{pmatrix}.$$

(9)

The gauge couplings $g_L$, $g_R$, and $g_B$ are related to the electromagnetic coupling $e$ by

$$\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g_R^2} + \frac{1}{g_B^2}.$$  

(11)

Assuming that $g_L = g_R$, we then have

$$g_L^2 = g_R^2 = \frac{e^2}{\sin^2 \theta_W}, \quad g_B^2 = \frac{e^2}{1 - 2 \sin^2 \theta_W},$$

(12)

where $\theta_W$ is the usual electroweak mixing angle.
It is clear from the above that the $10 \times 10$ mass submatrix spanning $\xi_0^i, \psi^0_1, S_3$, and the 3 gauge fermions will have 8 eigenvalues of order $\nu_3$ and 2 eigenvalues of order $m_{L,R,B}$. The $2 \times 2$ effective mass matrix spanning $S_1, S_2$ is then given by a generalized seesaw formula, i.e.

$$(M_S)_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3}\frac{2f_{k3}v_2(m_{ee})_{li}}{(m_{EE^c})_{kl}}. \quad (13)$$

If $f_{k3}$ are small enough, say less than $m_{ee}/v_2$, then $S_{1,2}$ may indeed be light enough to be considered as sterile neutrinos. Note that under the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group, $S \sim (1, 1, 0)$ is indeed a singlet.

We now have 5 light neutrinos, the usual ones $\nu_e, \nu_\mu, \nu_\tau$ with $R = +1$, and the sterile ones $S_{1,2}$ with $R = -1$. Since $R$ parity is still strictly conserved, they do not mix. Hence $S_{1,2}$ would not be a factor in considering the phenomenology of neutrino oscillations. However, as a discrete symmetry, $R$ parity may be broken by soft terms\cite{18} without affecting other essential properties of the unbroken theory. Remarkably, exactly such a soft term is allowed by the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$ gauge symmetry of this model, namely

$$m'_{ij}(\nu_i \psi^0_j - e_i E^c_j). \quad (14)$$

Hence the $3 \times 2$ matrix linking $\nu_e, \nu_\mu, \nu_\tau$ with $S_{1,2}$ is given by

$$(M_{\nu S})_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3}m'_{li}f_{k3}v_2(m_{EE^c})_{kl}, \quad (15)$$

and we have a general theoretical framework for considering 3 active and 2 sterile neutrinos.

Of course, further assumptions would be necessary to obtain a desirable pattern to explain the present observations of neutrino oscillations\cite{19, 20, 21}.

Given that $S_{1,2}$ are light, the fact that they are connected to $e^c_i$ through $W_R^\pm$ means that there are many modifications to the phenomenology of lepton weak interactions. One possibility is that $\nu_3$ is very large, then all such deviations are negligible. On the other hand, the analysis of Ref.\cite{11} shows that it is possible to have $\nu_3$ of order 1 TeV or less. This would
allow experiments in the near future to observe a number of exotic phenomena as discussed below.

Whereas the neutral gauge bosons of this model are flavor-diagonal in their couplings, the scalar bosons are not. Hence there will be some flavor-changing interactions, most of which are suppressed by Yukawa couplings. However, there is one important exception, i.e., those terms proportional to the top-quark mass. They appear in the superpotential as the following gauge-invariant combination:

$$u_i u_j^c \psi^0_k - d_i u_j^c E^c_k - u_i h_j^c e_k + d_i h_j^c \nu_k.$$  \hspace{1cm} (16)

It was pointed out a long time ago\[22\] that $\tilde{h}^c$ exchange would then contribute significantly to the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. As it happens, the first measurement\[23\] of this branching fraction, i.e.

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10},$$  \hspace{1cm} (17)

is in fact somewhat larger than the standard-model expectation\[24\], $(0.82 \pm 0.32) \times 10^{-10}$. If that is the correct interpretation, then using the results of Ref.\[22\], another prediction of this model is

$$\frac{B(b \rightarrow s \nu \bar{\nu})}{B(K^+ \rightarrow \pi^+ \nu \bar{\nu})} \simeq 2.4 \frac{|V_{tb}V_{us}|^2}{|V_{cb}V_{td}|^2},$$  \hspace{1cm} (18)

which is of order $10^5$. Hence the branching fraction of $b \rightarrow s \nu \bar{\nu}$ should be about $10^{-5}$, which is several orders of magnitude above the standard-model expectation.

Whereas the 2 light sterile neutrinos $S_{1,2}$ do not have standard-model interactions, they do transform nontrivially under $SU(2)_R \times U(1)$. Hence they must interact with the new heavy gauge bosons $W^\pm_R$ and

$$Z' = -\left(\frac{1 - 2x}{1 - x}\right)^{\frac{1}{2}} W^0_R + \left(\frac{x}{1 - x}\right)^{\frac{1}{2}} B,$$  \hspace{1cm} (19)

where $x \equiv \sin^2 \theta_W$. Consequently, there are several essential features of this model involving $S_{1,2}$.\[7\]
(A) The fundamental weak decay $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ is now supplemented with $\mu^- \rightarrow e^- S_i \bar{S}_j$ from $W_R^\pm$ exchange. The latter is constrained by present data[25] through the limit

$$|g_{VRR}| = \left(1 - U_{\mu 3}^2\right)^{\frac{1}{2}} \left(1 - U_{e 3}^2\right)^{\frac{1}{2}} \frac{m_{W_L}^2}{m_{W_R}^2} \left(1 - U_{\mu 3}^2\right)^{\frac{1}{2}} < 0.033,$$

where $S_e = U_{e1} S_1 + U_{e2} S_2 + U_{e3} S_3$, etc. and the matrix $U$ has been assumed real for simplicity.

(B) The flavor-changing decay $\mu \rightarrow eee$ gets tree-level contributions from Eq. (7) through $\tilde{\xi}_i^0$ exchange. However, they may be very small because the $f_{ijk}$’s may be chosen arbitrarily to suppress any such effect in this case. In contrast, there is an unavoidable one-loop contribution from the exchange of $W_R^\pm$ and $S_i$, which is the analog of the standard-model case of $W_L^\pm$ and $\nu_i$. Whereas the latter is totally negligible because it is proportional to neutrino mass-squared differences, the former is important because the mass of $S_3$ is comparable to $m_{W_R}$ but $S_{1,2}$ are essentially massless.

The largest exotic contribution to $\mu \rightarrow eee$ actually comes from the effective $Z\mu\bar{e}$ vertex. The reason is that in this model,

$$Z = (1 - x)^\frac{1}{2} W_L^0 - \left(\frac{x^2}{1 - x}\right)^\frac{1}{2} W_R^0 - \left(\frac{x - 2x^2}{1 - x}\right)^\frac{1}{2} B,$$

hence a new vertex $ZW_R^+ W_R^-$ appears, in analogy to $ZW_L^+ W_L^-$ of the standard model. The calculation of the one-loop $Z\mu\bar{e}$ vertex is similar to that of $Zd\bar{s}$[26] in the standard model. The result is $g_{Z\mu\bar{e}} Z^\lambda \bar{e}[\gamma_\lambda(1 + \gamma_5)/2]\mu$, with

$$g_{Z\mu\bar{e}} = \frac{e^3 U_{\mu 3} U_{e 3}}{16\pi^2 x^\frac{3}{2} (1 - x)^\frac{1}{2}} \left[ \frac{r_3}{1 - r_3} + \frac{r_3^2 \ln r_3}{(1 - r_3)^2} \right],$$

where

$$r_3 \equiv m_{S_3}^2 / m_{W_R}^2 = \left(1 - \frac{x}{1 - 2x}\right) \left(1 + \frac{v_2^2}{v_3^2}\right)^{-1}.$$

Hence this vertex is not suppressed at all, and its contribution to the $\mu \rightarrow eee$ decay amplitude is proportional to $1/m_Z^2$, so it is much larger than that of the box diagram from $W_R^\pm$ and $S_i$ exchange, which is proportional to $1/m_{W_R}^2$. 

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Connecting the $Z\mu\bar{e}$ vertex with the standard-model $Ze\bar{e}$ vertex, the decay branching fraction of $\mu \to eee$ is then given by

$$B(\mu \to eee) = 2x(1-x)(1-4x+12x^2)g_{Z\mu\bar{e}}^2/e^2.$$  \hspace{1cm} (24)$$

Since the present experimental upper limit\textsuperscript{25} of this is $1.0 \times 10^{-12}$, the following constraint is obtained:

$$U_{\mu 3}U_{e3} < 2.3 \times 10^{-3},$$  \hspace{1cm} (25)$$

where the $v_2^2/v_3^2$ term of Eq. (23) has been neglected.

(C) Because of Eq. (22), the rare decay $Z \to \mu^-e^+ + e^-\mu^+$ is also predicted. However, because of Eq. (25), its branching fraction is less than $8.6 \times 10^{-13}$ which is of course totally negligible. The analogous decays $Z \to \tau^-e^+ + e^-\tau^+$ and $Z \to \tau^-\mu^+ + \mu^-\tau^+$ are related to $\tau \to eee$, $\tau \to e\mu\mu$, $\tau \to \mu ee$, and $\tau \to \mu\mu\mu$, with upper limits\textsuperscript{25} of order $10^{-5}$ and $10^{-6}$ on their branching fractions respectively. All are predicted in this model to have branching fractions of order $10^{-7}$ multiplied by $U_{\tau 3}^2U_{e3}^2$ or $U_{\tau 3}^2U_{\mu 3}^2$.

(D) The archetypal rare decay $\mu \to e\gamma$ is also predicted in this model, again through $W^+_R$ and $S_i$ exchange. The one-loop diagrams are analogous to the usual ones in the standard model, resulting in a decay branching fraction

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left( \frac{m_{W_L}}{m_{W_R}} \right)^4 U_{\mu 3}^2U_{e3}^2F(r_3),$$  \hspace{1cm} (26)$$

where the function $F$ is given by\textsuperscript{27}

$$F(r_3) = \frac{r_3(-1 + 5r_3 + 2r_3^2)}{(1-r_3)^3} + \frac{6r_3^3\ln r_3}{(1-r_3)^4}.$$  \hspace{1cm} (27)$$

Using the most recent experimental upper bound\textsuperscript{28} of $1.2 \times 10^{-11}$ on $B$, we obtain

$$U_{\mu 3}U_{e3}(m_{W_L}^2/m_{W_R}^2) < 3.8 \times 10^{-4}.$$  \hspace{1cm} (28)$$
If the lightest exotic quark, call it $h_1$, is lighter than $W_R^\pm$, then its decay is predominantly given by

$$h_1 \rightarrow u_i e_j S_k.$$  \hspace{1cm} (29)

Since $S_{1,2}$ are light and undetected, this mimics the ordinary semileptonic decay of a heavy quark, but without any nonleptonic component.

In conclusion, the skew $E_6$ left-right model proposed many years ago\cite{3}, favored\cite{11} by recent atomic physics\cite{9} and $Z$ resonance\cite{10} data, has been shown to be a natural framework for 3 active and 2 sterile light neutrinos. The constraints from low-energy data, as given by Eqs. (20), (25), and (28), require at worst ($U_{\mu 3} = U_{e 3}$) only that $m_{W_R} > 442$ GeV, or equivalently $m_{S_3}(= m_{Z'}) > 528$ GeV. Hence the new physics of this model is accessible to experimental verification in the not-so-distant future.

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