LEPTOGENESIS: NEUTRINOS AND NEW LEPTON FLAVOR VIOLATION AT THE TEV ENERGY SCALE

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Abstract

Leptogenesis, i.e. the creation of a lepton asymmetry in the early Universe, may occur through the decay of heavy singlet (right-handed) neutrinos. If we require it not to be erased by physics beyond the Standard Model at the TeV energy scale, then only 2 candidates are possible if they are subgroups of $E_6$. These 2 solutions happen to be also the only ones within $1\sigma$ of the atomic parity violation data and the invisible $Z$ width. Lepton flavor violation is predicted in one model, as well as in another unrelated model of neutrino masses where the observable decay of a doubly charged scalar would determine the relative magnitude of each element of the neutrino mass matrix.

Talk given at the Joint U.S./Japan Workshop on New Initiatives in Lepton Flavor Violation and Neutrino Oscillations with Very Intense Muon and Neutrino Sources (Honolulu, HI), October 2-6, 2000.
1 Introduction

In the minimal Standard Model, leptons transform under $SU(3)_C \times SU(2)_L \times U(1)_Y$ according to

$$\begin{pmatrix} \nu \\ l \end{pmatrix}_L \sim (1, 2, -\frac{1}{2}), \quad l_R \sim (1, 1, -1). \quad (1)$$

In the absence of $\nu_R$, the Majorana mass of the neutrino must come from the effective dimension-5 operator [1]

$$\frac{1}{\Lambda} (\nu_i \phi^0 - l_i \phi^+) (\nu_j \phi^0 - l_j \phi^+). \quad (2)$$

This means that the so-called “seesaw” structure, i.e. $m_\nu \sim v^2/\Lambda$ is inevitable, no matter what specific mechanism is used to obtain $m_\nu$.

The canonical seesaw mechanism [2] is achieved with the addition of a heavy $N_R \sim (1, 1, 0)$. In that case, the interaction $f\bar{N}_R\nu_i\phi^0$ and the large Majorana mass $m_N$ of $N_R$ allow the above effective operator to be realized, with

$$m_\nu = \frac{f^2 \langle \phi^0 \rangle^2}{m_N} = \frac{m_D^2}{m_N}. \quad (3)$$

2 Leptogenesis from $N$ Decay

Consider the decay of $N$ in the early Universe. [3, 4] Since it is a heavy Majorana particle, it can decay into both $l^- \phi^+$ (with lepton number $L = 1$) and $l^+ \phi^-$ (with $L = -1$). Hence $L$ is violated. Now $CP$ may also be violated if the one-loop corrections are taken into account. Specifically, consider $N_1 \rightarrow l^- \phi^+$. This amplitude has contributions from the tree diagram as well as a vertex correction and a self-energy correction, with $l^+ \phi^-$ in the intermediate state and $N_{2,3}$ appearing in the cross and direct channels respectively. Calling this amplitude $A + iB$, where $A$ and $B$ are the dispersive and absorptive parts, the asymmetry generated
by $N_1$ decay is then proportional to

$$|A + iB|^2 - |A^* + iB^*|^2 = 4 \text{Im}(A^*B),$$

which is nonzero if $A$ and $B$ have a relative phase, i.e. if $CP$ is violated. Note that if there is only one $N$ (i.e. $N_{2,3}$ exchange is absent), then this phase is automatically zero in the above.

In the approximation that $M_1$ is much smaller than $M_{2,3}$, the decay asymmetry is

$$\delta \simeq \frac{G_F}{2\sqrt{2}} \frac{1}{(m_D^*m_D)_{11}} \sum_{j=2,3} \text{Im}(m_D^*m_D)_{ij}^2 \frac{M_1}{M_j},$$

which may be washed out by the inverse interactions which also violate $L$ unless the decay occurs out of equilibrium with the rest of the particles in the Universe as it expands. This places a constraint on $M_1$ to be in the range $10^9$ to $10^{13}$ GeV.

Once the $N$'s have decoupled as the Universe cools, the other (light) particles, i.e. those of the Standard Model, have only $L$ conserving interactions except for the nonperturbative sphalerons which violate $B + L$, but conserves $B - L$. Hence the $L$ asymmetry generated by $N$ decay gets converted into a baryon asymmetry of the Universe, which is observed at present to be of order $10^{-10}$.

If $N$ decay is indeed the source of this $B$ asymmetry (to which we owe our own very existence), then any TeV extension of the Standard Model should also conserve $B - L$. In the next section it will be shown that if this extension involves a subgroup of $E_6$, then there are only 2 possible candidates. 

3
3 Possible $E_6$ Subgroups at the TeV Scale

Consider the maximal subgroup $SU(3)_C \times SU(3)_L \times SU(3)_R$ of $E_6$. The fundamental $27$ representation is given by

$$27 = (3, 3, 1) + (3^*, 1, 3^*) + (1, 3^*, 3).$$

(6)

The fermions involved are all taken to be left-handed and defined to be

$$(u, d) \sim (3; 2, 1/6; 1, 0), \quad h \sim (3; 1, -1/3; 1, 0),$$

(7)

$$(d^c, u^c) \sim (3^*; 1, 0; 2, -1/6), \quad h^c \sim (3^*; 1, 0; 1, 1/3),$$

(8)

$$(\nu_e, e) \sim (1; 2, -1/6; 1, -1/3), \quad (e^c, N) \sim (1; 1, 1/3; 2, 1/6),$$

(9)

$$(E^c, N_E), (\nu_E, E) \sim (1; 2, -1/6; 2, 1/6), \quad S \sim (1; 1, 1/3; 1, -1/3),$$

(10)

under $SU(3)_C \times SU(2)_L \times U(1)_{Y_L} \times SU(2)_R \times U(1)_{Y_R}$. In this notation, the electric charge is given by $Q = T_{3L} + Y_L + T_{3R} + Y_R$, with $B - L = 2(Y_L + Y_R)$.

Since $(e^c, N)$ is an $SU(2)_R$ doublet, the requirement that $m_N > 10^9$ GeV for successful leptogenesis is not compatible with the existence of $SU(2)_R$ at the TeV scale. This rules out the subgroup $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ of $SO(10)$. However, as shown below, a different decomposition of $SU(3)_R$, i.e. into $SU(2)'_R \times U(1)_{Y'_R}$, with

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

(11)

allows $N$ to be trivial under the new skew left-right gauge group so that its existence at the TeV scale is compatible with $N$ leptogenesis.

To see how this works, consider the decomposition of $E_6$ into its $SO(10)$ and $SU(5)$ subgroups, then

$$27 = (16, 5^*)[d^c, \nu_e, e] + (16, 10)[u, d, u^c, e^c] + (16, 1)[N]$$

$$+ (10, 5^*)[h^c, \nu_E, E] + (10, 5)[h, E^c, N_E] + (1, 1)[S].$$

(12)
If we now switch \((16, 5^*)\) with \((10, 5^*)\) and \((16, 1)\) with \((1, 1)\), then the \(SU(5)\) content remains the same, but the \(SO(10)\) does not. The result is a different choice of the direction of \(SU(3)_R\) breaking, i.e. \(V\) spin instead of the usual \(T\) spin. Specifically, we switch \(d^c\) with \(h^c\), \((\nu_e, e)\) with \((\nu_E, E)\), and \(N\) with \(S\) in Eqs.\((8)\) to \((10)\). Now we may let \(N\) be heavy without affecting the new skew left-right gauge group

\[
SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}.
\]

Note that \(B - L\) is conserved by all the interactions of this model at the TeV scale.

Consider next the decomposition \(E_6 \rightarrow SO(10) \times U(1)_\psi\), then \(SO(10) \rightarrow SU(5) \times U(1)_\chi\), where

\[
Q_\psi = \sqrt{3/2} (Y_L - Y_R), \quad Q_\chi = \sqrt{1/10} (5T_{3R} - 3Y).
\]

The arbitrary linear combination \(Q_\alpha \equiv Q_\psi \cos \alpha + Q_\chi \sin \alpha\) has been studied extensively as a function of \(\alpha\). If we let \(\tan \alpha = 1/\sqrt{15}\), then \[8\]

\[
Q_N = \sqrt{1/40} (6Y_L + T_{3R} - 9Y_R).
\]

In that case, \(N\) is also trivial under this \(U(1)_N\). Hence

\[
SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N
\]

is the second and only other possible \(E_6\) extension of the Standard Model compatible with \(N\) leptogenesis.

4 New Neutral Currents and Lepton Flavor Violation

In the \(SU(3)_C \times SU(2)_L \times SU(2)'_R \times U(1)_{Y_L+Y'_R}\) model, \((h^c, u^c)\) and \((e^c, S)\) are \(SU(2)'_R\) doublets, but whereas \(u^c\) has \(B - L = -1/3\), \(h^c\) has \(B - L = 2/3\), and whereas \(e^c\) has \(B - L = 1\), \(S\) has \(B - L = 0\), hence the \(W'_R\) gauge boson of this model has \(B - L = -1\)
(because \( T'_{3R} = -1 \) and \( Y'_R = 0 \) imply \( Y_R = -1/2 \)). This unusual property has been studied extensively. Moreover, if \( S \) is light, it may be considered a “sterile” neutrino. In that case, it has recently been shown [9] that \( M_{W_R} > 442 \) GeV.

The extra neutral gauge boson \( Z' \) of this model is related to \( W_R \) by

\[
M_{Z'} = (\cos \theta_W / \cos 2\theta_W) M_{W_R} > 528 \text{ GeV},
\]

and it couples to \([10]\)

\[
\frac{1}{\sqrt{1 - 2x}} [xT_{3R} + (1 - x)T'_{3R} - xQ]
\]

\[= \frac{-1}{\sqrt{1 - 2x}} [xY_L + \left(\frac{3x - 1}{2}\right) T_{3R} - \left(\frac{3 - 5x}{2}\right) Y_R],
\]

where \( x \equiv \sin^2 \theta_W \) and \( g_L = g_R \). The \( Z \) boson of this model behaves in the same way as that of the Standard Model, except

\[
Z = \sqrt{1 - x} W_L^0 + \frac{x}{\sqrt{1 - x}} W_R^0 - \frac{\sqrt{x} \sqrt{1 - 2x}}{\sqrt{1 - x}} B,
\]

which implies a \( ZW^+_R W^-_R \) coupling that is absent in the Standard Model.

Together with the \( Z' \) of the \( U(1)_N \) model, the extra neutral-current interactions of these two \( E_6 \) subgroups are the only ones within 1\( \sigma \) of the atomic parity violation data [11] and the invisible \( Z \) width. [12] [The \( U(1)_N \) model was not considered in Ref. [12], 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.] The remarkable convergence of the requirement of successful \( N \) leptogenesis and the hint from present neutral-current data regarding possible new physics at the TeV scale is an encouraging sign for the validity of one of these models.

Because of the \( ZW^+_R W^-_R \) coupling, lepton flavor violation occurs in one loop through the effective \( Z\bar{e}\mu \) vertex. This is the analog of the \( ZW^+_L W^-_L \) contribution in the Standard Model. The latter is negligible because all the neutrino masses are very small; the former is
not because $m_{S_3} = M_{Z'}$ in the simplest supersymmetric version of this model. The effective $\mu - e$ transition coupling is then given by

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

(20)

where $r_3 = m_{S_3}^2 / M_{W_R}^2 = 1.426$ and $S_{1,2}$ are assumed light.

Using present experimental bounds, upper limits of the mixing of $S_3$ to $\mu$ and $e$ are given below.

$$|U_{\mu 3} U_{e 3}| < 2.3 \times 10^{-3} \text{ from } B(\mu \rightarrow eee) < 1.0 \times 10^{-12};$$

(21)

$$|U_{\mu 3} U_{e 3}| < 3.6 \pm 0.9 \times 10^{-3} \text{ [} \mu - e \text{ conversion in } ^{48}Ti, \ ^{208}Pb];$$

(22)

$$|U_{\mu 3} U_{e 3}| \frac{M_{W_L}^2}{M_{W_R}^2} < 3.8 \times 10^{-4} \text{ from } B(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}. \quad (23)$$

This shows that unless the mixing angles are extremely small, future precision experiments on lepton flavor violation will be able to test this model in conjunction with TeV colliders.

## 5 New Verifiable Model of Neutrino Masses

Let us go back to the effective operator of Eq. (2) and rewrite it as

$$\frac{1}{\Lambda} [\nu_i \nu_j \phi^0 \phi^0 - (\nu_i \nu_j + \nu_i l_j) \phi^0 \phi^+ + l_i l_j \phi^+ \phi^+] + h.c. \quad (\text{24})$$

This tells us that another natural realization of a small Majorana neutrino mass is to insert a heavy scalar triplet $\xi = (\xi^{++}, \xi^+, \xi^0)$ with couplings to leptons

$$f_{ij}[\xi^0 \nu_i \nu_j + \xi^+(\nu_i l_j + l_i \nu_j)/\sqrt{2} + \xi^{++} l_i l_j] + h.c., \quad (\text{25})$$

and to the standard scalar doublet

$$\mu[\bar{\xi}^0 \phi^0 \phi^0 - \sqrt{2} \xi^- \phi^+ \phi^0 + \xi^{-} \phi^+ \phi^+] + h.c. \quad (\text{26})$$
We then obtain \[ m_\nu = \frac{2 f_{ij} \mu \langle \phi^0 \rangle^2}{m_{\xi}^2} = 2 f_{ij} \langle \xi^0 \rangle. \] (27)

This shows the inevitable seesaw structure, but instead of identifying \( m_N \) with the large scale \( \Lambda \) as in the canonical seesaw model \[4\], we now require only \( m_{\xi}/\mu \) to be large. If \( \mu \) is sufficiently small, the intriguing possibility exists for \( m_\xi \) to be of order 1 TeV and be observable at future colliders. The decay

\[ \xi^{++} \rightarrow l_i^+ l_j^+ \] (28)

is easily detected and its branching fractions determine the relative \( |f_{ij}| \)'s, i.e. the 3 \( \times \) 3 neutrino mass matrix up to phases and an overall scale. \[14\] This possible connection between collider phenomenology and neutrino oscillations is an extremely attractive feature of the proposed Higgs triplet model of neutrino masses.

To understand why \( \mu \) can be so small and why \( m_\xi \) should be of order 1 TeV, one possibility \[14\] is to consider the Higgs triplet model in the context of large extra dimensions. \( \mu \) is small here because it violates lepton number and may be represented by the “shining” of a singlet scalar in the bulk, i.e. its vacuum expectation value as felt in our brane. \( m_\xi \) is of order 1 TeV because it should be less than the fundamental scale \( M_* \) in such theories which is postulated to be of order a few TeV.

Lepton flavor violation in this model may now be predicted if we know \( f_{ij} \). Using a hierarchical neutrino mass matrix which fits present atmospheric \[15\] and solar \[16\] neutrino oscillations (choosing the large-angle MSW solution), we predict \[14\] \( \mu - e \) conversion to be easily observable at the MECO experiment as shown in Fig. 1 if \( m_\xi \) is indeed of order 1 TeV. The dimensionless parameter \( h \) there is proportional to \( \mu \).
6 Conclusion

Leptogenesis, neutrino masses, lepton flavor violation, and new physics at future colliders are most likely intertwined. They may well be the different colors of a rainbow (manoa) and must exist together or not at all.

Acknowledgments

I thank Y. Kuno and W. Molzon for a very useful and stimulating Workshop. This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837.

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Figure 1: Rate of $\mu - e$ conversion in $^{13}$Al.