FERMION MASSES AND NEUTRINO OSCILLATIONS IN 
$SO(10) \times SU(2)_F$*

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We present in this talk a model based on $SO(10) \times SU(2)_F$ having symmetric mass textures with 5 zeros constructed by us recently. The symmetric mass textures arising from the left-right symmetry breaking chain of $SO(10)$ give rise to good predictions for the masses, mixing angles and CP violation measures in the quark and lepton sectors (including the neutrinos), all in agreement with the most up-to-date experimental data within $1\sigma$. Various lepton flavor violating decays in our model are also investigated. Unlike in models with lop-sided textures, our prediction for the decay rate of $\mu \rightarrow e\gamma$ is much suppressed and yet it is large enough to be probed by the next generation of experiments. The observed baryonic asymmetry in the Universe can be accommodated in our model utilizing soft leptogenesis.

1. Introduction

$SO(10)$ has long been thought to be an attractive candidate for a grand unified theory (GUT) for a number of reasons: First of all, it unifies all the 15 known fermions with the right-handed neutrino for each family into one 16-dimensional spinor representation. The seesaw mechanism then arises very naturally, and the small yet non-zero neutrino masses can thus be explained. Since a complete quark-lepton symmetry is achieved, it has the promise for explaining the pattern of fermion masses and mixing. Recent atmospheric neutrino oscillation data from Super-Kamiokande indicates non-zero neutrino masses. This in turn gives very strong support to the viability of

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SO(10) as a GUT group. Models based on SO(10) combined with discrete or continuous family symmetry have been constructed to understand the flavor problem. Most of the models utilize “lopsided” mass textures which usually require more parameters and therefore are less constrained. The right-handed neutrino Majorana mass operators in most of these models are made out of $16_H \times 16_H$ which breaks the R-parity at a very high scale. The aim of this talk, based on Ref. [2-4], is to present a realistic model based on supersymmetric SO(10) combined with SU(2) family symmetry which successfully predicts the low energy fermion masses and mixings. Since we utilize symmetric mass textures and 126-dimensional Higgs representations for the right-handed neutrino Majorana mass operator, our model is more constrained in addition to having R-parity conserved. We also investigate several lepton flavor violating (LFV) processes in our model as well as soft leptogenesis.

2. The Model

There are so far no fundamental understandings of the origin of flavor have been found. A less ambitious aim is to reduce the number of parameters by imposing texture assumptions. We concentrate on symmetric mass matrices as they are more predictive and can arise naturally if SO(10) is broken to the SM with the left-right symmetry at the intermediate scale. Naively one would expect that there are six texture zeros for symmetric quark mass matrices because there are six non-zero quark masses. It has been shown that this does not work and in order to obtain viable predictions, there can at most be five texture zeros. We consider the following combination for the up- and down-type quark Yukawa matrices with five zeros, which reads, after removing all the non-physical phases by rephasing various matter fields:

$$Y_{u,\nu L,R} = \begin{pmatrix} 0 & 0 & a \\ 0 & b e^{i\theta} & c \\ a & c & 1 \end{pmatrix} d \quad (1)$$

$$Y_{d,e} = \begin{pmatrix} 0 & c e^{-i\xi} & 0 \\ c e^{i\xi} (1, -3) f & 0 \\ 0 & 0 & 1 \end{pmatrix} h \quad (2)$$

The above texture combination can be realized by utilizing an $SU(2)_F$ family symmetry. In order to specify the superpotential uniquely, we invoke
\[ Z_2 \times Z_2 \times Z_2 \] discrete symmetry. The matter fields are
\[ \psi_a \sim (16, 2)^{-++} \quad (a = 1, 2), \quad \psi_3 \sim (16, 1)^{+++} \]

where \( a = 1, 2 \) and the subscripts refer to family indices; the superscripts 
\(+/-\) refer to \((Z_2)^3\) charges. The Higgs fields which break \( SO(10) \) and give
rise to mass matrices upon acquiring VEV’s are
\[(10, 1) : \quad T_1^{+++, T_2^{+-}, T_3^{--}, T_4^{--}, T_5^{---}} \]
\[(126, 1) : \quad C^{----}, \quad \overline{C}^{+++}, \quad \overline{C}^{++-}. \]

Higgs representations 10 and \( 126 \) give rise to Yukawa couplings to the
matter fields which are symmetric under the interchange of family indices.
\( SO(10) \) is broken through the left-right symmetry breaking chain, and sym-
metric mass matrices and the following intra-family relations arise,
\[ M_u \sim Y_{10}^{10} \langle 10^+ \rangle + Y_{126}^{126} \langle 126^+ \rangle \]  
\[ M_d \sim Y_{10}^{10} \langle 10^- \rangle + Y_{126}^{126} \langle 126^- \rangle \]
\[ M_e \sim Y_{10}^{10} \langle 10^- \rangle - 3Y_{126}^{126} \langle 126^- \rangle \]
\[ M_{\nu LR} \sim Y_{10}^{10} \langle 10^+ \rangle - 3Y_{126}^{126} \langle 126^+ \rangle \]

The \( SU(2) \) family symmetry is broken in two steps and the mass hierarchy
is produced using the Froggatt-Nielsen mechanism: \( SU(2) \xrightarrow{\epsilon M} U(1) \xrightarrow{\epsilon'} M \) nothing
where \( M \) is the UV-cutoff of the effective theory above which the
family symmetry is exact, and \( \epsilon M \) and \( \epsilon' M \) are the VEV’s accompanying
the flavon fields given by
\[ (1, 2) : \quad \phi^{++}_1, \quad \phi^{+-}_2, \quad \Phi^{-+}, \quad (1, 3) : \quad S^{+-}_1, \quad S^{--}_2, \quad \Sigma^{++}. \]

The vacuum alignment in the flavon sector is given by
\[ \langle \phi^{(1)} \rangle = \begin{pmatrix} \epsilon' \\ 0 \end{pmatrix}, \quad \langle \phi^{(2)} \rangle = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix} \]
\[ \langle S^{(1)} \rangle = \begin{pmatrix} 0 & \epsilon' \\ \epsilon' & 0 \end{pmatrix}, \quad \langle S^{(2)} \rangle = \begin{pmatrix} 0 & 0 \\ 0 & \epsilon \end{pmatrix} \]
\[ \langle \Phi \rangle = \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix}, \quad \langle \Sigma \rangle = \begin{pmatrix} 0 & 0 \\ 0 & \delta_2 \end{pmatrix}. \]

The various aspects of VEV’s of Higgs and flavon fields are given in Ref.
[2-4].
The superpotential of our model is

\[ W = W_{\text{Dirac}} + W_{\nu RR} \]  

\[ W_{\text{Dirac}} = \psi_3 \psi_3 T_1 + \frac{1}{M} \psi_3 \psi_a (T_2 \phi_{(1)} + T_3 \phi_{(2)}) \]
\[ + \frac{1}{M} \psi_a \psi_b (T_4 + \bar{C}) S_{(2)} + \frac{1}{M} \psi_a \psi_b T_{(1)} \]
\[ W_{\nu RR} = \psi_3 \psi_3 C_1 + \frac{1}{M} \psi_3 \psi_a \bar{\Psi} C_2 + \frac{1}{M} \psi_a \psi_b \Sigma C_2. \]  

The mass matrices then can be read from the superpotential to be

\[ M_{\text{a, LR}} = \begin{pmatrix} 0 & 0 & \langle 10^+ \rangle \epsilon' \\ 0 & \langle 10^+ \rangle \epsilon & \langle 10^+ \rangle \epsilon \\ \langle 10^+ \rangle \epsilon' & \langle 10^+ \rangle \epsilon & \langle 10^+ \rangle \epsilon \\ \end{pmatrix} = \begin{pmatrix} 0 & 0 & r_2 \epsilon' \\ 0 & r_4 \epsilon & \epsilon \\ r_2 \epsilon' & \epsilon & 1 \\ \end{pmatrix} M_U \]  

\[ M_{d,e} = \begin{pmatrix} 0 & \langle 10^- \rangle \epsilon' \\ \langle 10^- \rangle \epsilon' & (1, -3) \langle \bar{126} \rangle \epsilon & 0 \\ 0 & 0 & \langle 10^- \rangle \epsilon \\ \end{pmatrix} = \begin{pmatrix} 0 & \epsilon' & 0 \\ \epsilon' & (1, -3) \epsilon p & 0 \\ 0 & 0 & 1 \end{pmatrix} M_D \]  

where \( M_U = \langle 10^+ \rangle \), \( M_D = \langle 10^- \rangle \), \( r_2 = \langle 10^+_2 \rangle / \langle 10^+_1 \rangle \), \( r_4 = \langle 10^+_4 \rangle / \langle 10^+_1 \rangle \) and \( p = \langle \bar{126} \rangle / \langle 10^- \rangle \). The right-handed neutrino mass matrix is

\[ M_{\nu RR} = \begin{pmatrix} 0 & 0 & \langle 126_0^0 \rangle \delta_1 \\ 0 & \langle 126_0^0 \rangle \delta_2 & \langle 126_0^0 \rangle \delta_3 \\ \langle 126_0^0 \rangle \delta_1 & \langle 126_0^0 \rangle \delta_2 & \langle 126_0^0 \rangle \delta_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \delta_1 \\ 0 & \delta_2 & \delta_3 \\ \delta_1 & \delta_2 & \delta_3 \end{pmatrix} M_R \]  

with \( M_R = \langle 126_1^0 \rangle \). Here the superscripts +/-/0 refer to the sign of the hypercharge. It is to be noted that there is a factor of \(-3\) difference between the (22) elements of mass matrices \( M_d \) and \( M_e \). This is due to the CG coefficients associated with \( \bar{126} \), as a consequence, we obtain the phenomenologically viable Georgi-Jarlskog relation. We then parameterize the Yukawa matrices as given in Eq. (1) and (2).
We use the following as inputs at $M = 91.187\, GeV$:

\[
\begin{align*}
m_u &= 2.21\, MeV (2.33^{+0.42}_{-0.45}) \\
m_c &= 682\, MeV (677^{+56}_{-61}) \\
m_t &= 181\, GeV (181^{+13}_{-13}) \\
m_e &= 0.486\, MeV (0.486847) \\
m_\mu &= 103\, MeV (102.75) \\
m_\tau &= 1.74\, GeV (1.7467) \\
|V_{us}| &= 0.225(0.221 - 0.227) \\
|V_{ub}| &= 0.00368(0.0029 - 0.0045) \\
|V_{cb}| &= 0.0392(0.039 - 0.044)
\end{align*}
\]

where the values extrapolated from experimental data are given inside the parentheses. Note that the masses given above are defined in the modified minimal subtraction (MS) scheme and are evaluated at $M_Z$. These values correspond to the following set of input parameters at the GUT scale, $M_{GUT} = 1.03 \times 10^{16}\, GeV$, and $\tan \beta = 10$:

\[
\begin{align*}
a &= 0.00250, & b &= 3.26 \times 10^{-3} \\
c &= 0.0346, & d &= 0.650 \\
\theta &= 0.74 \\
e &= 4.036 \times 10^{-3}, & f &= 0.0195 \\
h &= 0.06878, & \xi &= -1.52 \\
g_1 &= g_2 = g_3 = 0.746
\end{align*}
\]

the one-loop renormalization group equations for the MSSM spectrum with three right-handed neutrinos are solved numerically down to the effective right-handed neutrino mass scale, $M_R$. At $M_R$, the seesaw mechanism is implemented. With the constraints $|m_{\nu_3}| \gg |m_{\nu_2}|, |m_{\nu_1}|$ and maximal mixing in the atmospheric sector, the up-type mass texture leads us to choose the following effective neutrino mass matrix

\[
M_{\nu LL} = \begin{pmatrix}
0 & 0 & t \\
0 & 1 & 1 + t^n \\
t & 1 + t^n & 1 \\
\end{pmatrix} \frac{d^2 v^2}{M_R^2} \quad (12)
\]
with \( n = 1.15 \), and from the seesaw formula we obtain

\[
\delta_1 = \frac{a^2}{r} \quad (13)
\]

\[
\delta_2 = \frac{b^2 t e^{2\theta}}{r} \quad (14)
\]

\[
\delta_3 = -\frac{a(be^{i\theta}(1 + t^{1.15}) - c) + bcte^{i\theta}}{r} \quad (15)
\]

where \( r = (c^2 t + a^2 t^{0.15}(2 + t^{1.15}) - 2a(-1 + c + ct^{1.15})) \). A generic feature of mass matrices of the type given in Eq.(12) is that they give rise to bi-large mixing pattern. And the value of \(|U_{e3}|^2\) is proportional to the ratio of \( \Delta m^2_{\odot} \) to \( \Delta m^2_{\text{atm}} \).

We then solve the two-loop RGE’s for the MSSM spectrum down to the SUSY breaking scale, taken to be \( m_t(m_t) = 176.4 \) GeV, and then the SM RGE’s from \( m_t(m_t) \) to the weak scale, \( M_Z \). We assume that \( \tan \beta \equiv v_u/v_d = 10 \), with \( v_u^2 + v_d^2 = (246/\sqrt{2} \text{ GeV})^2 \). At the weak scale \( M_Z \), the predictions for \( \alpha_i = g_i^2/4\pi \) are

\[
\alpha_1 = 0.01663, \quad \alpha_2 = 0.03374, \quad \alpha_3 = 0.1242 .
\]

These values compare very well with the values extrapolated to \( M_Z \) from the experimental data, \( (\alpha_1, \alpha_2, \alpha_3) = (0.01696, 0.03371, 0.1214 \pm 0.0031) \). The predictions at the weak scale \( M_Z \) for the charged fermion masses, CKM matrix elements and strengths of CP violation, are summarized in Table. The predictions for the charged fermion masses, the CKM matrix elements and the CP violation measures. The predictions of our model in this updated fit are in good agreement with all experimental data within 1\( \sigma \), including much improved measurements in B Physics that give rise to precise values for the CKM matrix elements and for the unitarity triangle. Note that we have taken the SUSY threshold correction to \( m_b \) to be \(-18\%\).

The allowed region for the neutrino oscillation parameters has been reduced significantly after Neutrino 2004. Using the most-up-to-date best fit values for the mass square difference in the atmospheric sector \( \Delta m^2_{\text{atm}} = 2.33 \times 10^{-3} \) eV\(^2\) and the mass square difference for the LMA solution \( \Delta m^2_{\odot} = 8.14 \times 10^{-5} \) eV\(^2\) as input parameters, we determine \( t = 0.344 \) and \( M_R = 6.97 \times 10^{12} \text{GeV} \), which yield \( (\delta_1, \delta_2, \delta_3) = (0.00120, 0.000703 e^{(1.47)}, 0.0210 e^{(0.175)}) \). We obtain the following predictions in the neutrino sector: The three mass eigenvalues are give by

\[
(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) = (0.00262, 0.00939, 0.0492) \text{ eV} .
\]
Table 1. The predictions for the charged fermion masses, the CKM matrix elements and the CP violation measures.

|                         | experimental results | predictions at $M_Z$ |
|-------------------------|----------------------|---------------------|
| $m_s/m_d$               | $17 \sim 25$         | 25                  |
| $m_s$                   | $93.4^{+11.8}_{-13.6} MeV$ | $86.0 MeV$          |
| $m_b$                   | $3.00 \pm 0.11 GeV$  | $3.03 GeV$          |
| $|V_{ud}|$               | $0.9739 - 0.9751$    | 0.974               |
| $|V_{cd}|$               | $0.221 - 0.227$      | 0.225               |
| $|V_{cs}|$               | $0.0048 - 0.014$     | 0.00801             |
| $|V_{ts}|$               | $0.037 - 0.043$      | 0.0386              |
| $|V_{tb}|$               | $0.9990 - 0.9992$    | 0.999               |
| $|V_{td}|$               | $(2.88 \pm 0.33) \times 10^{-5}$ | $2.87 \times 10^{-5}$ |
| $\sin 2\alpha$         | $-0.16 \pm 0.26$     | -0.048              |
| $\sin 2\beta$          | $0.736 \pm 0.049$    | 0.740               |
| $\gamma$               | $60^0 \pm 14^0$      | $64^0$              |
| $\beta$                | $0.20 \pm 0.09$      | 0.173               |
| $\tau$                 | $0.33 \pm 0.05$      | 0.366               |

The prediction for the MNS matrix is

$$|U_{MNS}| = \begin{pmatrix}
0.852 & 0.511 & 0.116 \\
0.427 & 0.560 & 0.710 \\
0.304 & 0.652 & 0.695 \\
\end{pmatrix}$$ (17)

which translates into the mixing angles in the atmospheric, solar and reactor sectors,

$$\sin^2 2\theta_{atm} = \frac{4|U_{\mu 3}|^2|U_{\tau 3}|^2}{(1 - |U_{e 3}|^2)^2} = 1.00$$ (18)

$$\tan^2 \theta_\odot = \frac{|U_{e 2}|^2}{|U_{e 1}|^2} = 0.36$$ (19)

$$\sin^2 \theta_{13} = |U_{e 3}|^2 = 0.0134 \, .$$ (20)

The prediction of our model for the strengths of CP violation in the lepton sector are

$$J_{CP}^L \equiv Im\{U_{11}^* U_{12}^* U_{21}^* U_{22}\} = -0.00941$$ (21)

$$(\alpha_{31}, \alpha_{21}) = (0.934, -1.49) \, .$$ (22)
Using the predictions for the neutrino masses, mixing angles and the two Majorana phases, $\alpha_{31}$ and $\alpha_{21}$, the matrix element for the neutrinoless double $\beta$ decay can be calculated and is given by $|\langle m \rangle| = 3.1 \times 10^{-3}$ eV, with the present experimental upper bound being 0.35 eV. Masses of the heavy right-handed neutrinos are

$$M_1 = 1.09 \times 10^7 \text{GeV} \quad (23)$$

$$M_2 = 4.53 \times 10^9 \text{GeV} \quad (24)$$

$$M_3 = 6.97 \times 10^{12} \text{GeV}. \quad (25)$$

The prediction for the $\sin^2 \theta_{13}$ value is 0.0134, in agreement with the current bound 0.015 at 1σ. Because our prediction for $\sin^2 \theta_{13}$ is very close to the present sensitivity of the experiment, the validity of our model can be tested in the foreseeable future.

3. Lepton Flavor Violating Decays and Soft Leptogenesis

Non-zero neutrino masses imply lepton flavor violation. If neutrino masses are induced by the seesaw mechanism, new Yukawa coupling involving the RH neutrinos can induce flavor violation. Observable decay rates can be obtained if the relevant scale for these LFV operators is the SUSY scale. We consider LFV decays resulting from the non-vanishing off-diagonal matrix elements in the slepton mass matrix induced by the RG corrections between $M_{GUT}$ and $M_R$. In this case, the branching ratios for the decay of $\ell_i \rightarrow \ell_j + \gamma$ is

$$Br(\ell_i \rightarrow \ell_j \gamma) = \frac{\alpha^3 \tan^2 \beta}{16\pi} \frac{1}{(3m_0^2 + A_0^2)^2} \left| \sum_{k=1,2,3} (Y_{\nu})_{ik}(Y_{\nu})_{kj} \ln \left( \frac{M_{GUT}}{M_{R_{\ell}}} \right) \right|^2.$$  

(26)

In our model, $Br(\mu \rightarrow e\gamma) < Br(\tau \rightarrow e\gamma) < Br(\tau \rightarrow \mu\gamma)$ is predicted. Our predictions for the branching ratio of the decay $\mu \rightarrow e\gamma$ arising from the RG effects induced by neutrino Dirac Yukawa couplings as a function of the gaugino mass $M_{1/2}$ is given in Fig. 1. In contrast to the predictions of models with lop-sided textures, in which the off-diagonal elements in (23) sector of $M_e$ are of order $O(1)$ leading to an enhancement in the decay branching ratio and the need of some new mechanism to suppress the decay rate of $\mu \rightarrow e\gamma$, the predictions of our model for LFV processes, $\ell_i \rightarrow \ell_j \gamma$, $\mu-e$ conversion as well as $\mu \rightarrow 3e$, are well below the most stringent bounds up-to-date. Our predictions for many processes are nonetheless within the reach of the next generation of LFV searches. This is especially true for $\mu - e$ conversion and $\mu \rightarrow e\gamma$. More details are contained in Ref. [5].
Soft leptogenesis (SFTL) utilizes the soft SUSY breaking sector, and the asymmetry in the lepton number is generated in the decay of the superpartner of the RH neutrinos. The lepton number asymmetry is then converted to the baryonic asymmetry by the sphaleron effects. The source of CP violation in the lepton number asymmetry in SFTL is due to the CP violation in the mixing which occurs when the following relation \( \text{Im}(A_1 \frac{M_1}{B}) \neq 0 \) (\( A \) and \( B \) are the tri-linear \( A \)-term and \( B \)-term) is satisfied. The total lepton number asymmetry integrated over time, \( \epsilon \), is defined as the ratio of difference to the sum of the decay widths \( \Gamma \) for \( \bar{\nu}_{R_1} \) and \( \bar{\nu}_{R_1}^\dagger \) into final states of the slepton doublet \( \bar{\nu} \) and the Higgs doublet \( H \), or the lepton doublet \( L \) and the higgsino \( \tilde{H} \) or their conjugates,

\[
\epsilon = \frac{\sum_f \int_0^\infty \left[ \Gamma(\bar{\nu}_{R_1}, \bar{\nu}_{R_1}^\dagger \rightarrow f) - \Gamma(\bar{\nu}_{R_1}, \bar{\nu}_{R_1}^\dagger \rightarrow \overline{f}) \right]}{\sum_f \int_0^\infty \left[ \Gamma(\bar{\nu}_{R_1}, \bar{\nu}_{R_1}^\dagger \rightarrow f) + \Gamma(\bar{\nu}_{R_1}, \bar{\nu}_{R_1}^\dagger \rightarrow \overline{f}) \right]} \quad (27)
\]

where \( f \) denotes the final states \( (\bar{L} H), (L \bar{H}) \) and \( \overline{f} \) denotes their conjugate, \( (\bar{L}^1 H^1), (\overline{L} \overline{H}) \). This leads to a total amount of baryon asymmetry in our model due to soft leptogenesis is,

\[
\frac{n_B}{s} \simeq -1.48 \times 10^{-3} \left( \frac{\text{Im}(A)}{M_1} \right) \frac{4 \Gamma_1 B}{\Gamma_1^2 + 4 B^2} \delta_{B-F} \kappa. \quad (28)
\]

In Fig. 2, we show the predictions for the asymmetry, \( n_B/s \), as a function of \( B' \) for different values of \( \text{Im}(A) \). With \( B' \sim 1 \text{ TeV} \) and \( \text{Im}(A) \sim 1 \text{ TeV} \), sufficient baryonic asymmetry can be generated. More details are contained in Ref. [5].

4. Conclusion

To conclude, the observed fermion mass hierarchy and mixing have been successfully accommodated in our model utilizing the two-step breaking in \( SU(2)_F \). Due to the SO(10) and \( SU(2)_F \) symmetries and the resulting symmetric mass textures, the number of parameters in the Yukawa sector has been significantly reduced. With 11 parameters, our model gives rise to values for 12 masses, 6 mixing angles and 4 CP violating phases, all in agreements with available experimental data within 1 \( \sigma \). In contrast to the predictions of models with lop-sided textures, the predictions of our model for LFV processes, \( \ell_i \rightarrow \ell_j \gamma, \mu - e \) conversion as well as \( \mu \rightarrow 3e \), are well below the most stringent bounds up-to-date, and yet many of them are within the reach of the next generation of LFV searches. The observed baryonic asymmetry in the Universe can be accommodated in our model utilizing soft leptogenesis.
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Figure 1. The branching ratio of \( \mu \to e \gamma \) as a function of the gaugino mass \( M_{1/2} \), for various values of scalar masses, \( m_0 \) and \( A_0 \): (S1): \( m_0 = A_0 = 100 \) GeV; (S11): \( m_0 = 100 \) GeV, \( A_0 = 1 \) TeV; (S2): \( m_0 = A_0 = 500 \) GeV; (S3): \( m_0 = A_0 = 1 \) TeV.

Figure 2. The prediction for \( n_B/s \) as a function of \( B' \) for \( |Im(A)| = 10 \) TeV, 5 TeV and 1 TeV.