NEUTRINO MIXING IN SO(10)

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ABSTRACT

We present the calculation of neutrino mixing in SO(10) Grand Unified Theory with three families of fermions. The neutrino mass is assumed to be generated either at the tree level using explicit $\underset{\sim}{126}$ representation of Higgs (via Gell-Mann-Ramond-Slansky mechanism), or at the two loop level as suggested by Witten. We find only large $\nu_\mu - \nu_\tau$ mixing, with all mixing angles given by the up quark mass ratios.

1. INTRODUCTION

A great many experiments are now in progress to measure neutrino masses and oscillations. In addition to non-zero, non-degenerate masses, observation of neutrino oscillations need substantial mixing among the neutrinos. It is interesting to see what the Grand Unified Theories (GUT) can say about the magnitude of this mixing. In this talk, I shall discuss the calculation of neutrino mixing based on the SO(10) GUT.[1] An interesting model of neutrino mixing based on SU(5) GUT is discussed in reference 2. Before we go to the actual calculation of mixing in section 4, we briefly discuss in section 2 and 3, how the neutrinos acquire small masses in SO(10), and the constraints imposed on the Higgs sector by the quark-lepton mass ratios and mixing angles.

2. NEUTRINO MASS IN SO(10)

In SU(5) GUT, the 15 left-handed fermions in each generation are assigned to the representations $\underset{\sim}{5}^*$ and $\underset{\sim}{10}$. If only $\underset{\sim}{24}$ and $\underset{\sim}{5}$ (and/or $\underset{\sim}{45}$) representations of Higgs are used to break the symmetry down to $SU(3)_c \times U(1)$, there is a global symmetry, B-L which forbids neutrino mass generation to any order in perturbation theory.[3] Majorana mass can be generated using the Higgs representation, $\underset{\sim}{15}$. But, in that case, the neutrino mass matrix is not related to the quark mass matrix. Hence, the neutrino mixing angles, expressed in terms of neutrino masses, remain unknown.

In SO(10) GUT, the fermions are assigned in the spinor representation $\underset{\sim}{16}$ which has the SU(5) decomposition, $\underset{\sim}{16} = \underset{\sim}{5}^* + \underset{\sim}{10} + \underset{\sim}{1}$. Thus, in addition to the known 15 left-handed fermions, an extra singlet neutral lepton, ν_L^c ($\bar{\nu}_L^c \equiv \nu_R$) is introduced. The fermion masses arise from the product, $\underset{\sim}{16} \times \underset{\sim}{16} = \underset{\sim}{10} + \underset{\sim}{126} + \underset{\sim}{120}$. Only the representation $\underset{\sim}{126}$ contain an SU(5) singlet, and can be used to give large Majorana mass to this neutral singlet lepton.[4] The usual left-handed neutrino acquire a Dirac-type mass equal (1/3) to the up quark mass from the Higgs representation $\underset{\sim}{10}(\underset{\sim}{126})$.[5] Thus, for a single generation, the neutrino mass matrix becomes[4]

$$\begin{array}{c|cc} & \nu_L & \nu_L^c \\ \hline \nu_L & 0 & m_q \\ \nu_L^c & m_q & M_R \end{array} \quad . \tag{1}$$

For $m_q \ll M_R$, the diagonalization of (1) gives $m_{\nu_R} \sim M_R$, $m_{\nu_L} \sim m_q^2/M_R$. The SO(10) symmetry breaking chain that we consider here is

$$SO(10) \xrightarrow{45_H} SU(4) \times SU(2) \times U(1) \xrightarrow{126_H(\underset{\sim}{1})} SU(3)_c \times SU(2) \times U(1) \xrightarrow{10_H \text{ and/or } 126_H} SU(3)_c \times U(1) \ .$$

The analysis of $\sin^2\theta_W$ indicates[6] that the scale of $126_H(1)$ breaking is $\sim 10^{12}$ GeV. Thus, in SO(10), not only the observed left-handed neutrino acquires a small mass, this mechanism[4] explains why it is so small compared to the quark mass.

It has been pointed out[7] that it is not necessary to introduce a non-zero $\langle \underset{\sim}{126}(\underset{\sim}{1}) \rangle$ to get a small neutrino mass. Consider the SO(10) symmetry breaking chain,

$$SO(10) \xrightarrow{16_H} SU(5) \xrightarrow{45_H} SU(3)_c \times SU(2) \times U(1) \xrightarrow{10_H \text{ and/or } 126_H} SU(3)_c \times U(1) \quad .$$

In this case, there will be a trilinear coupling of the form $16_H\, 10_H\, 16_H$, unless forbidden by imposing a discrete symmetry. Let us write the trilinear coupling as $\varepsilon g M\, 16_H\, 10_H\, 16_H$, where g is the gauge coupling, and M is the mass scale associated with the symmetry breaking by 16_H. Then, since $\underset{\sim}{10} \times \underset{\sim}{45} \times \underset{\sim}{45}$ contains $\underset{\sim}{126}$, the right-handed neutrino, ν_R acquires a mass at the two loop level.[7] The mass is estimated to be[7]

$$M_{\nu_R} = \varepsilon \left(\frac{\alpha}{\pi}\right)^2 \left(\frac{m_q}{m_W}\right) M \quad . \tag{2}$$

M is expected to lie between 10^{14} - 10^{19} GeV.

We point out that the relation $m_{\nu_L} \sim m_q^2/M_{\nu_R}$ follows from fairly general grounds[8] that the lowest dimensional $SU(3)_c \times SU(2) \times U(1)$-invariant operator that violate lepton number conservation is of

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dimension 5. The relation $m_{\nu_L} \sim m_\ell^2/m_{W_R^\pm}$ was also derived[9] in the $SU(2)_L \times SU(2)_R \times U(1)$ gauge model.

In SO(10) GUT, whether the neutrino mass is generated using explicit $\underset{\sim}{126}(\underset{\sim}{1})$ representation of Higgs or via radiative correction, the neutrino mass matrix is determined[10] in terms of up quark mass matrix, except for the exact overall scale. So, we shall be able to calculate the neutrino mixing angles in terms of the up quark mass ratios.

3. QUARK-LEPTON MASS RATIOS AND MIXING ANGLES

The quark-lepton mass relations[11] which seem to work experimentally are

$$m_\mu/m_e = 9\, m_s/m_d\,, \quad m_\tau = m_b \quad \text{at } M \sim 10^{15}\text{ GeV}. \tag{3}$$

To derive (3), it is necessary to use both $\underset{\sim}{5}$ and $\underset{\sim}{45}$ representations of Higgs[11,12] in SU(5), and both $\underset{\sim}{10}$ and $\underset{\sim}{126}$ representations[6] in SO(10). In SO(10), the relations (3) can be obtained from the following Yukawa interactions:

$$\begin{aligned}\mathcal{L}_Y = (a\ 16_1\ 16_2 + b\ 16_3\ 16_3)\,10 + e\ 16_2\ 16_2\ \overline{126}_2 \\ + c\ 16_2\ 16_3\ \overline{126}_3 + \text{h.c.} \qquad .\end{aligned} \tag{4}$$

Here 16_i represent the left-handed fermions in the i^{th} generation, 10, 126_2 and 126_3 represent different Higgs scalars, and a, b, c, e are real coupling constants. It is assumed that 126_2 and 126_3 have vacuum expectation values along $\underset{\sim}{45}$ and $\underset{\sim}{\bar 5}$ of SU(5). (4) can be obtained by writing down the most general Yukawa couplings for the above fermions and the Higgs scalars, and then imposing the invariance under the following discrete symmetry:

$$\begin{aligned} &16_1 \to \eta^a\, 16_1\,, \quad 16_2 \to \eta^b\, 16_2\,, \quad 16_3 \to \eta^{\frac12(a+b)}\, 16_3 \\ &10 \to \eta^{-(a+b)}\, 10\,, \quad \overline{126}_2 \to \eta^{-2b}\, \overline{126}_2\,, \quad \overline{126}_3 \to \eta^{-(\frac12 a+\frac32 b)}\, 126_3\,. \end{aligned} \tag{5}$$

The up-quark, down-quark and lepton mass matrices obtained from (4) are

$$M^u = \begin{pmatrix} 0 & a & 0 \\ a & 0 & c \\ 0 & c & b \end{pmatrix}, \quad M^d = \begin{pmatrix} 0 & d & 0 \\ d & e & 0 \\ 0 & 0 & f \end{pmatrix}, \quad M^\ell = \begin{pmatrix} 0 & d & 0 \\ d & -3e & 0 \\ 0 & 0 & f \end{pmatrix}. \tag{6}$$

The parameters a, b, c, d, e and f in (6) are defined to be the parameters appearing in (4) times the vacuum expectation values of the corresponding Higgs fields. The mass relations (3) follows from (6). The predictions for the Kobayashi-Maskawa mixing angles are[6,11,12]

$$s_1 \sim (m_d/m_s)^{\frac12}\,, \quad s_2 \sim -(m_c/m_t)^{\frac12}\,, \quad s_3 \sim -(m_u/m_t)^{\frac12}\, s_1^{-1}\,. \tag{7}$$

In our calculation of neutrino mixing in SO(10), we shall assume that the Yukawa couplings for the quark and the leptonic sector are given by (4).

4. NEUTRINO MIXING

For three families, the 6 × 6 neutrino mass matrix can be expressed as

$$M^\nu = \begin{pmatrix} L & \nu \\ \nu & R \end{pmatrix} \tag{8}$$

which refers to the neutrino fields written as $\psi = (\nu_e, \nu_\mu, \nu_\tau, \nu_e^c, \nu_\mu^c, \nu_\tau^c)$ where c means change conjugate. L and R are 3 × 3 Majorana mass matrices for the light and heavy neutrinos, and ν contains Dirac type mass terms. The Yukawa interaction (4) gives,

$$L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \nu = \begin{pmatrix} 0 & a & 0 \\ a & 0 & -3c \\ 0 & -3c & b \end{pmatrix}, \quad R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{9}$$

It is clear that $\mathcal{L}_Y$ in (4) must be modified in such a way that the right-handed Majorana sector, R must be non-zero, and all three right-handed neutrinos acquire superheavy masses. We would like to keep L = 0 in order not to lose the prediction for the light neutrino masses and their mixing. Since all three right-handed Majorana neutrinos have to be superheavy, we need at least two parameters in R, and the two possible forms of R are

$$\begin{aligned} R_1 &= \begin{pmatrix} 0 & A & 0 \\ A & 0 & 0 \\ 0 & 0 & B \end{pmatrix}, \text{ or } \begin{pmatrix} B & 0 & 0 \\ 0 & 0 & A \\ 0 & A & 0 \end{pmatrix} \\ R_2 &= \begin{pmatrix} 0 & 0 & A \\ 0 & B & 0 \\ A & 0 & 0 \end{pmatrix}. \end{aligned} \tag{10}$$

Both R_1 and R_2 gives eigenvalues (-A, A, B). Now, we discuss how such R's can be generated naturally using I) explicit $\underset{\sim}{126}(\underset{\sim}{1})$ coupling in $\mathcal{L}_Y$, or II) via radiative correction.

CASE I. R GENERATED BY EXPLICIT $\underset{\sim}{126}(\underline{1})$ COUPLING

Majorana sector R_1 is generated by adding $\mathcal{L}_{Y'}$ to the $\mathcal{L}_Y$ in (4).[13]

$$\mathcal{L}_{Y'} = (A\ 16_1\ 16_2 + B\ 16_3\ 16_3)\ 126_1 \quad . \tag{11}$$

126_1 transform like $\underset{\sim}{10}$ under the discrete symmetry in (5), and has non-zero vacuum expectation value only along the $\underline{1}$-direction in SU(5). Then, the mass matrices M^u, M^d and M^ℓ obtained from $\mathcal{L}_Y + \mathcal{L}_{Y'}$ are the same as in (6). The 6 × 6 neutrino mass matrix now becomes[13,14]

$$M^\nu = \begin{pmatrix} 0 & \nu \\ \nu & R_1 \end{pmatrix} \tag{12}$$

where ν is given in (9) and R_1 in (10). The parameters a, b and c are determined by the up quark masses,

$$a \sim (m_u\ m_c)^{1/2}\ , \quad b \sim m_t\ , \quad c \sim (m_c\ m_t)^{1/2} \quad . \tag{13}$$

The only unknown parameters are A and B. The neutrino masses and mixing angles are obtained by diagonalizing[15] M^ν in (12). The eigenvalues,[14] with the assumption A ~ B, are approximately

$$\lambda_1 = -a^3b/18c^2A\ , \quad \lambda_2 = 18abc^2/(b^2+9c^2)A\ , \quad \lambda_3 = -(b^2+9c^2)/B\ ,$$
$$\lambda_4 = -A\ , \quad \lambda_5 = A\ , \quad \lambda_6 = B\ . \tag{14}$$

Using the values of a, b and c from (13), the three light neutrino masses are,

$$\begin{aligned} m_{\nu_1} &= -\lambda_1 \simeq m_u(m_u\ m_c)^{1/2}/18\ A \\ m_{\nu_2} &= \lambda_2 \simeq 18\ m_c(m_u\ m_c)^{1/2}/A(1+9\ m_c/m_t) \\ m_{\nu_3} &= -\lambda_3 \simeq m_t^2(1+9\ m_c/m_t)/B \quad . \end{aligned} \tag{15}$$

For A ~ B, we have the hierarchy of neutrino masses.

The mixing among the light neutrinos is given by $\nu_\alpha = U_{\alpha i}\nu_i$ where ν_α, $\alpha = e,\mu,\tau$ correspond to the eigenstates of weak currents, and ν_i, $i = 1,2,3$ correspond to the mass eigenstates. Expressed in Kobayashi-Maskawa form,[16] (with CP-violating phase δ put = 0), we obtain[14] from (12)-(15),

$$U = \begin{pmatrix} 1 & \theta_1 & 0 \\ -c_2\theta_1 & c_2 & s_2 \\ \theta_1 s_2 & -s_2 & c_2 \end{pmatrix} \tag{16}$$

where

$$\begin{aligned} \theta_1 &\simeq -(m_u/m_c)^{1/2}\ (1+9\ m_c/m_t)^{1/2}/18 \\ \tan\theta_2 &\simeq 3(m_c/m_t)^{1/2}\ , \quad \theta_3 \simeq 0 \quad . \end{aligned} \tag{17}$$

Thus the mixing between ν_μ and ν_τ could be large, whereas all other mixing angles are very small.

We point out that our charged lepton mass matrix, M^ℓ in (6) is not diagonal. If we consider the mixing matrix for the coupling of the neutrinos to charged leptons, then this produces an additional mixing of $-(m_e/m_\mu)^{1/2}$ between ν_e and ν_μ.

The Majorana sector, R_2 can be obtained naturally by adding $\mathcal{L}_{Y''} = A\ 16_1\ 16_3\ \overline{126}_1 + B\ 16_2\ 16_2\ \overline{126}_4$ to $\mathcal{L}_Y$ in (4). Here both $\overline{126}_1$ and $\overline{126}_4$ are assumed to have non-zero vacuum expectation values only along $\underline{1}$ of SU(5). In this case, all mixing angles among the light neutrinos come out to be small, of the order of $(m_u/m_c)^{1/2}$ and $(m_u/m_t)^{1/2}$.

CASE II. RIGHT-HANDED MAJORANA SECTOR, R GENERATED BY RADIATIVE CORRECTION

Here we do not introduce any explicit $126(\underline{1})$ Higgs representation. So the right-handed neutrinos do not acquire any mass at the tree level. However, they acquire masses at the two loop level,[7] due to trilinear couplings of 16_H with 10_H and/or $\overline{126}_H$, as discussed in section 2. The Yukawa couplings, $\mathcal{L}_Y$ are taken to be the same as given in (4). Since we have one $\underset{\sim}{10}$ and two 126_H in (4), the most general trilinear Higgs couplings with 16_H are

$$\mathcal{L}_t = gM\ 16_H(\varepsilon_1\ 10_H + \varepsilon_2\ \overline{126}_{2H} + \varepsilon_3\ \overline{126}_{3H})\ 16_H \quad . \tag{18}$$

However $\underset{\sim}{10}$, $\overline{126}_2$ and $\overline{126}_3$ transform differently under discrete symmetry, (5). So only one of ε_1, ε_2 and ε_2 can be non-zero. It is easy to see that if ε_2 or ε_3 is non-zero, the Majorana sector, R generated does not give superheavy masses to all three right-handed neutrinos. So we choose the transformation of 16_H under the discrete symmetry, (5) such that only the ε_1-term in (18) survives. Then, the right-handed Majorana sector, R generated at the two loop level is

$$R = K \begin{pmatrix} 0 & a & 0 \\ a & 0 & 0 \\ 0 & 0 & b \end{pmatrix} \tag{19}$$

where $K = \varepsilon_1\left(\frac{\alpha}{\pi}\right)^2 M/m_W$.

We see that except for the overall scale, K, the Majorana sector, R gets determined in terms of the parameters of the up quark mass matrix, (6). The ratio A/B for R_1 in (10), which was arbitrary in case I, is now determined, $A/B = a/b = (m_u\ m_c)^{1/2}/m_t$.

The radiative correction at the two loop level also give direct contribution to the light neutrino masses. These contributions have been estimated,[17] and are found to be suppressed by the factor

$(m_W/M)^2$ relative to the right-handed masses. For the present case, these give

$$L = K'\begin{pmatrix} 0 & a & 0 \\ a & 0 & 0 \\ 0 & 0 & b \end{pmatrix} \quad (20)$$

where $K' = (m_W/M)^2 K$.

A detail account of our results for the neutrino mixing via Witten's mechanism[7] will be presented elsewhere.[18] Here, we give the results for the present model taking $L = 0$.

For the light neutrino masses, we obtain,

$$m_{\nu_1} = a^2 b/27\,Kc^2 \ , \quad (21)$$

$$m_{\nu_3, \nu_2} = (b^2+9c^2)[\pm 1 + (1 + 108 b^2c^2/(b^2+9c^2)^2)^{1/2}]/2Kb \ .$$

where a, b and c are given in (13). Thus light neutrino masses are completely determined in terms of up quark masses, except for the overall scale, K. There is a hierarchy between m_{ν_1} and m_{ν_2}; however m_{ν_2} and m_{ν_3} could be comparable. If the factor $108\, b^2c^2/(b^2+9\,c^2)^2$ is << 1, then we get complete hierarchy, $m_{\nu_1}: m_{\nu_2}: m_{\nu_3} = m_u: m_c: m_t$.

The mixing angles among the light neutrinos expressed in the Kobayashi-Maskawa form, (16) is obtained to be

$$\tan\theta_2 = 6c[1 + (b^2+9\,c^2)\{-1 + (1+108\,b^2c^2/(b^2+9\,c^2)^2)^{1/2}\}/2b^2]^{-1}/b$$

$$\sin\theta_1 \simeq -\,ab/27\,c^2 \cos\theta_2 \ . \quad (22)$$

θ_2 depends only on the ratio (m_c/m_t) which could be determined from the bottom quark decays in our model [see equation (7)]. Mixing of the electron neutrino is again small; while $\nu_\mu - \nu_\tau$ mixing could be large. For $m_c = 1.5$ GeV, $m_t = 30$ GeV, $m_u = 5$ MeV, (22) gives $\theta_2 \simeq 39°$ and $\theta_1 \simeq -0.6°$.

CONCLUSION

In the SO(10) GUT, it is natural for the light neutrinos to have small masses in the range 10^{-6} eV - 10^3 eV. A hierarchy of neutrino masses, similar to the hierarchy of quark masses is plausible, though not a must. Assuming a reasonable quark-lepton phenomenology, the mixing of the electron type neutrino is always predicted to be small. The mixing between ν_μ and ν_τ could be large, depending on the yet unknown ratio, (m_c/m_t). The present data[19] excludes maximal $\nu_\mu - \nu_\tau$ mixing for $\Delta m^2 > 3$ eV^2. We encourage the experimentals to push their limits further, which would test this interesting aspect of the SO(10) theory.

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19. See talk by T. Kondo in this conference. For a detailed discussion of the neutrino oscillation phenomenology, see talk by V. Barger in this conference, and also the references cited there.

NEUTRINO OSCILLATIONS AND
NEUTRINO-ELECTRON SCATTERING†

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ABSTRACT

We point out that neutrino flavor oscillations can significantly alter the cross section for neutrino-electron scattering. As a result, such oscillations can affect the comparison between existing reactor data and theories of neutral-current processes. They may also lead to strikingly large effects in high-energy accelerator experiments.

One expects that, in general, neutral-current processes will be completely unaffected by the oscillation of neutrinos among their various possible flavors (ν_e, ν_μ, ν_τ,...). After all, these processes presumably preserve neutrino flavor, and are independent of that flavor. Thus, oscillation of neutrinos from one flavor to another will not change any neutral-current cross sections. Indeed, even if the neutral weak interactions do change neutrinos ν_f of one flavor (e.g., ν_e) into those of another, if they do so through amplitudes of the form

$$a(\nu_f A \to \nu_{f'} B) = N_{f'f}\bar{a} \quad , \tag{1}$$

where $N_{f'f}$ is a unitary matrix and $\bar{a}$ is a universal amplitude, neutrino oscillations will still have no effect. (The unitarity of $N_{f'f}$ guarantees that the interactions remain independent of flavor in the sense that the total cross section for a neutrino ν_f to interact, $\sum_{f'} \sigma(\nu_f A \to \nu_{f'} B)$, does not depend on the incoming flavor.)

There is one exception to all this; namely, neutrino- (or antineutrino-) electron scattering.[A] For all neutrino flavors but ν_e, this reaction is a purely neutral-current process. However, for this one flavor, the reaction receives both neutral- and charged-current contributions, as illustrated in Fig. 1. Since the charged-

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