Systematic Study Of Leptonic Mixing In A Class Of SU$_H$(2) Models.

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We perform a systematic analysis of the PMNS matrices which arise when one assigns the three generations of leptons to the $2 \oplus 1$ representation of a horizontal $SU_H(2)$ symmetry. This idea has been previously explored by Kuchimanchi and Mohapatra. However, we assume (i) the neutrino mass matrix results from leptonic couplings to $SU_L(2)$ triplet scalar fields and (ii) hierarchies exist amongst lepton mass matrix elements which result from couplings to scalar fields with different $SU_H(2)$ charges. Of the sixteen candidate PMNS matrices which result it is found that only one is both predictive and possesses a leading order structure compatible with experimental data. The relevant neutrino mass matrix displays the symmetry $L_e - L_\mu - L_\tau$ to leading order and we explore the perturbations required to produce a realistic lepton spectrum. The effective mass in neutrinoless double beta decay is required to lie in the range $< m > / (10^{-2} \text{eV}) \in [0.7, 2.5]$, which is just below current experimental bounds.

$U_{e3}$ is non-zero but not uniquely determined.

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I. INTRODUCTION

The search for a possible connection between the observed families of fermions, the properties possessed by the fermions, and an underlying horizontal symmetry has a long history (see for example [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]). In more recent years, the experimental observation of neutrino mixing has lead to an enormous amount of research into a link between the bi-large mixing in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and a horizontal symmetry. In particular, some recent works [21, 22, 23] have attempted to relate the observed values of the PMNS matrix to the structure enforced upon the lepton mass matrices by an $SU_H(2)$ symmetry.

In this paper we perform a systematic analysis of the PMNS mixing matrices that arise when the three lepton families are assigned to the $2 \oplus 1$-representations of $SU_H(2)$, and the neutrino mass matrix results from couplings of the $SU_L(2)$ doublet leptons to $SU_L(2)$ triplet scalar fields. The main purpose of the study is to attempt to relate the observed PMNS matrix structure to a high energy $SU_H(2)$ symmetry. This idea has been previously explored by Kuchimanchi and Mohapatra (KM) [21, 22] by extending the scalar sector to include the necessary $SU_L(2)$ triplet fields. In this case the horizontal symmetry breaking scale must be large enough, or the relevant coupling constants small enough, to render the seesaw contributions to the neutrino mass matrix contributions

$\frac{<m>}{10^{-2} \text{eV}} \in [0.7, 2.5]$, (1)
Alternatively one may consider a model where the neutrino field $N_R$, an $SU_H(2)$ doublet of right-chiral neutrinos, is not present. The field $N_R$ was necessary in the KM models to remove the global anomaly. One could instead consider a model with a gauge group $G_{SM} \otimes G_{SM} \otimes SU_H(2)$, where $G_{SM}$ is the standard model (SM) gauge group, $G_{SM}$ describes a mirror sector and the horizontal symmetry couples the two sectors. This would allow the groups $G_{SM}$ and $G_{SM}$ to each possess an odd number of $SU_H(2)$ doublets whilst the entire theory is free of the global anomaly. In this way mathematical consistency of the model would not necessitate the structure of the mass matrix for the light neutrino mixing matrix may not be as direct. The see-saw mechanism dictates certain structures directly upon the neutrino Majorana mass matrix. This is because the horizontal symmetry may differentiate in some sense between the electron generation and the mu and tau generations. The matrix (4) arises from a perturbation upon a mixing matrix with the bi-maximal structure may be attributed to the absence, or weaker coupling to, certain scalar representations of the gauge group. Similarly by setting $s_1, t_{1,2,3} = 0$ one obtains a mass matrix with the same zeros as (5) so again this structure may be obtained by consideration of the scalar content of a given model. The quasi-degenerate spectrum can also be approximated by (2) if $d_{1,2} = 0$ and $t_3 > t_{1,2}$, though the correlation between the

$$U_{BM} = \begin{pmatrix} 1 & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

There are three particularly interesting leading order mass matrices which lead to bi-maximal mixing:

- The normal hierarchy, $m_3 \gg m_{2,1}$, occurs when

$$M_\nu \approx \frac{\Delta m^2_{31}}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}. \quad (4)$$

where $\Delta m^2_{31}$ is the atmospheric mass-squared difference. This matrix possesses the flavour symmetry $L_e$ and results in maximal mixing in the 2-3 sector.

- One obtains an inverted hierarchy, $m_2 \approx m_1 \gg m_3$, when

$$M_\nu \approx \frac{\Delta m^2_{21}}{2} \begin{pmatrix} 0 & -1 & 1 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \quad (5)$$

This mass matrix produces exactly the bi-maximal form of the mixing matrix. It conserves the flavour symmetry $L_e$ and results in maximal mixing in the 2-3 sector.

Matrices of this type have been considered previously in [30, 31, 32]. This matrix possess an $L_\mu - L_\tau$ symmetry, which brought it to the attention of the authors of [33, 34, 35]. It is interesting to note a feature which is common to each of the mass matrices (4), (5) and (6).

- Quasi-degenerate neutrinos, $m_1 \approx m_2 \approx m_3$, are obtained when:

$$M_\nu \approx m \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}. \quad (6)$$

The matrices of this type have been considered previously in [30, 31, 32].
We denote the scalar vacuum expectation values (VEV’s) as

\[ <\chi> = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} \sqrt{\frac{1}{2}} & <\chi_2> \\ <\chi_3> & -\frac{1}{\sqrt{2}} \end{pmatrix}, \quad (10) \]

\[ <\phi> = \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad <\Phi> = \begin{pmatrix} 0 \\ \kappa_1 \\ \kappa_2 \end{pmatrix}. \quad (11) \]

The mass Lagrangian becomes

\[ \mathcal{L}_{M_L} = \bar{L'}_L M_i L'_R + \text{h.c.} + \ldots, \quad (12) \]

where \( L' = (e', \mu', \tau')^T \), the dots represent interaction terms and

\[ M_i = \begin{pmatrix} g_2 v & -g_3 \kappa_2 & g_3 \kappa_1 \\ g_2 \kappa_1 & g_1 \sqrt{\frac{1}{2}} + g_4 v & g_4 <\chi_1> \\ g_2 \kappa_2 & g_4 <\chi_3> & -g_4 \sqrt{\frac{1}{2}} + g_1 v \end{pmatrix}. \quad (13) \]

To simplify notation we denote this by

\[ M_i = \begin{pmatrix} S_2 & D_3 & D_4 \\ D_3 & T_2 + S & T_1 \\ D_4 & T_3 & -T_2 + S \end{pmatrix}. \quad (14) \]

where the entries labelled \( S, D \) and \( T \) arise from scalars forming singlet, doublet and triplet representations of \( SU_H(2) \).

The most general neutrino mass Lagrangian is

\[ \mathcal{L}_{M_{\nu}} = f \bar{\Psi} c \Delta_2 \psi_{\nu} + f_1 \bar{\Psi} c \Delta_3 \Psi + f_2 \bar{\Psi} c \Delta_1 \psi_{\nu} + \text{h.c.}, \quad (15) \]

where

\[ \Delta_1 \sim (3, 2, 1), \quad \Delta_2 \sim (3, 2, 2), \quad \Delta_3 \sim (3, 2, 3). \quad (16) \]

The charge conjugate fermion fields are defined as \( \psi^c_{\nu} = \epsilon C \psi_{\nu} \) and \( \psi^c = C \epsilon \psi^c \) where \( C \) is the Dirac space charge conjugation matrix. Observe that the Lagrangian \( \mathcal{L}_{M_{\nu}} \) does not contain a term of the type \( \Psi^c \Delta_1 \Psi \). The scalars must acquire VEV’s in the electrically neutral direction and we may denote these VEV’s as \( <\Delta_1^o>, <\Delta_2^o>, <\Delta_3^o>, <\Delta_3^o> \) etc.

The Lagrangian \( \mathcal{L}_{M_{\nu}} \) may be rewritten as

\[ \mathcal{L}_{M_{\nu}} = \bar{L'}_{\nu} M_{\nu} L_{\nu'} + \text{h.c.} + \ldots \quad (17) \]

where \( L_{\nu'} = (\nu_{\nu'L}, \nu_{\nu' L}, \nu_{\nu' T})^T \) and

\[ M_{\nu} = \begin{pmatrix} f_2 <\Delta_1^o> & -f <\Delta_2^o> & f <\Delta_1^o> \\ -f <\Delta_2^o> & -f_1 <\Delta_1^o> & f_1 <\Delta_3^o> \\ f <\Delta_1^o> & f_1 <\Delta_2^o> & f_1 <\Delta_3^o> \end{pmatrix}. \]

Again, to simplify notation we write

\[ M_{\nu} = \begin{pmatrix} s_1 & d_1 & d_2 \\ d_1 & t_1 & t_2 \\ d_2 & t_2 & t_3 \end{pmatrix}, \quad (18) \]

with the entries labelled \( s, d \) and \( t \) resulting from couplings to \( SU_L(2) \) triplet fields which form singlet, doublet and triplet representations of \( SU_H(2) \) respectively.

The mass matrices \( [14] \) and \( [13] \) demonstrate the relationship between the structure of the lepton mass matrices and the scalar content in the class of models we are studying. In the next section we study the leading order PMNS matrices obtained under assumed hierarchies within the matrices \( [14] \) and \( [13] \).
IV. DETERMINING THE PMNS MIXING MATRIX

Certain assumptions regarding the hierarchy of elements within the lepton mass matrices have been made for the purpose of our analysis. We now discuss these assumptions.

We study the PMNS matrices obtained when one assumes hierarchies of the type $|d| \gg |s| \gg |t|$, $|T| \gg |S| \gg |D|$ etc, where we collectively label all entries resulting from couplings with $SU_H(2)$ singlets, doublets and triplets in the neutrino (charged lepton) sector by $s$, $d$ and $t$ ($S$, $D$ and $T$) respectively. Without an assumption of this type the mass matrices are very general and are unlikely to leave a signature of the horizontal symmetry. The choice of this type of hierarchy rests on the idea that the given leptons may uniformly couple more strongly/weakly to a given scalar representation than others, or that there is a hierarchy amongst the VEV’s of the different representations. It may be unnecessary to include a given scalar in a realistic model if it is found that mass matrix entries arising from this particular scalar are not required to produce realistic mixing. Deviations from this type of hierarchy are considered when it is either physically motivated or presents no significant complication of the overall mixing matrix.

During our analysis we shall retain only two of the three distinctive scalar representations in each of the lepton sectors. The representations absent from the analysis may be considered to contribute sub-dominantly to a given mass matrix or may not be necessary in model construction. To simplify matters we shall take all mass matrix elements to be real.

The investigations are structured as follows. We begin by obtaining the leading form of the charged lepton mixing matrix $U_1$, where

$$U_1 M_1 U_1^T = \text{diag}(m_e^2, m_u^2, m_d^2).$$

The matrix $U_1$ is determined for various assumed hierarchies of the elements of $M_1$. The neutrino mixing matrix $U_\nu$, where

$$U_\nu M_\nu U_\nu^T = M_\nu^d = \text{diag}(m_1, m_2, m_3),$$

is then determined under the assumed hierarchies of elements of $M_\nu$. The various combinations of the matrices $U_1$ and $U_\nu$ are then combined to determine the resulting PMNS matrix $U$, where $U = U_1 U_\nu^T$.

We now present an example analysis for the charged lepton and neutrino sectors. We shall present the details for the case which turns out to be most interesting. The results for the other cases can be found in the table below.

The most general charged lepton mass matrix is

$$M_l = \begin{pmatrix} S_2 & D_3 & D_4 \\ D_1 & T_2 + S & T_1 \\ D_2 & T_3 & -T_2 + S \end{pmatrix}. \quad (19)$$

We shall refer to the $SU_L(2)$ doublet scalars $\phi$, $\Phi$ and $\chi$ respectively as the singlet, doublet and triplet scalars. Consider the case when only the singlet and triplet scalars are retained. In this case the mass matrix is

$$M_l = \begin{pmatrix} S_2 & 0 & 0 \\ 0 & T_2 + S & T_1 \\ 0 & T_3 & -T_2 + S \end{pmatrix}. \quad (20)$$

One cannot take $S \gg T_{1,2,3}, S_2$ as this produces $m_\mu \approx m_\tau$. The size of $S_2$ relative to $T_{1,2,3}, S$ allows two possibilities. If one takes $S_2 \gg T_{1,2,3}, S$ then

$$U_1^A = \begin{pmatrix} 0 & c_A & -s_A \\ 0 & s_A & c_A \\ 1 & 0 & 0 \end{pmatrix}, \quad (21)$$

whilst for $T_{1,2,3} \gg S, S_2$ or $T_{1,2,3}, S \gg S_2$ one has

$$U_1^B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_B & -s_B \\ 0 & s_B & c_B \end{pmatrix}, \quad (22)$$

where we have adopted the notation $c_X = \cos \theta_X$, $s_X = \sin \theta_X$ and

$$\tan 2\theta_A = \frac{2(T_3(T_2 + S) + T_1(S - T_2))}{T_3^2 - T_2^2 - 4T_2S}. \quad (23)$$

For the case of $T_{1,2,3} \gg S, S_2$ one may also make the approximation

$$\tan 2\theta_B \approx \frac{2T_3}{T_2 + T_1}. \quad (24)$$

If one instead retains the triplet and doublet scalars the mass matrix is

$$M_l = \begin{pmatrix} 0 & D_3 & D_4 \\ D_1 & T_2 & T_1 \\ D_2 & T_3 & -T_2 \end{pmatrix}. \quad (25)$$

Under the hierarchy $T \gg D$ one may write

$$M_l M_l^T \approx \begin{pmatrix} 0 & D_1T_2 + D_4T_1 & D_3T_3 - D_1T_2 \\ D_1T_2 + D_4T_1 & 0 & 0 \\ D_3T_3 - D_1T_2 & 0 & 0 \end{pmatrix} + O(D^2), \quad (26)$$

and treat the second matrix as a perturbation. The zeroth order mixing matrix is

$$U_1^F = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_F & -s_F \\ 0 & s_F & c_F \end{pmatrix}, \quad (27)$$

The representations absent from the analysis may be considered sub-dominantly to a given mass matrix or may not be necessary in model construction. To simplify matters we shall take all mass matrix elements to be real.

The investigations are structured as follows. We begin by obtaining the leading form of the charged lepton mixing matrix $U_1$, where

$$U_1 M_1 U_1^T = \text{diag}(m_e^2, m_u^2, m_d^2).$$

The matrix $U_1$ is determined for various assumed hierarchies of the elements of $M_1$. The neutrino mixing matrix $U_\nu$, where

$$U_\nu M_\nu U_\nu^T = M_\nu^d = \text{diag}(m_1, m_2, m_3),$$

is then determined under the assumed hierarchies of elements of $M_\nu$. The various combinations of the matrices $U_1$ and $U_\nu$ are then combined to determine the resulting PMNS matrix $U$, where $U = U_1 U_\nu^T$.

We now present an example analysis for the charged lepton and neutrino sectors. We shall present the details for the case which turns out to be most interesting. The results for the other cases can be found in the table below.
where
\[ \tan 2\theta_F = \frac{2T_2}{T_3 + T_1} = \frac{\sqrt{2} < \chi_2 >}{< \chi_3 > + < \chi_1 >}. \] (28)

Note that \( \theta_F \) is equal to \( \theta_{AB} \) in the limit \( S \to 0 \) and that \( U_F \) has the same form as \( U_{I_B} \). When one includes the perturbation in \( \mathcal{O} \), \( U_F \) will acquire some corrections. Ultimately, however, the gross structure of \( U_I \) in this case will be set by \( U_F \). Thus the doublet-triplet case with \( T \gg D \) is very similar to the singlet-triplet case with \( T \gg S \). The singlet-triplet case with \( T \gg S \) allows only \( 2 - 3 \) mixing in the charged lepton sector. The doublet provides more free parameters and allows sub-dominant mixing to occur between the \( 2 - 3 \) states and the first state.

We now consider an example of the neutrino mixing analysis. We shall now refer to \( \Delta_1, \Delta_2 \) and \( \Delta_3 \) as the singlet, doublet and triplet scalars, labelling them by their \( SU(2)_H \) transformation properties. The most general mass matrix is

\[ M_\nu = \begin{pmatrix} s_1 & d_1 & d_2 \\ d_1 & t_1 & t_2 \\ d_2 & t_2 & t_3 \end{pmatrix}, \] (29)

and we investigate the dominant mixing that results from hierarchies between the elements labelled \( s, d \) and \( t \). As an example we consider the case \( d \gg s \). Retaining the singlet and doublet scalars results in the neutrino mass matrix

\[ M_\nu = \begin{pmatrix} s_1 & d_1 & d_2 \\ d_1 & 0 & 0 \\ d_2 & 0 & 0 \end{pmatrix}. \] (30)

This matrix has two non-zero eigenvalues

\[ \lambda_\pm = \frac{1}{2} \left( s_1 \pm \sqrt{s_1^2 + 4(d_1^2 + d_2^2)} \right), \] (31)

and one zero eigenvalue. Upon defining

\[ N_\pm = \frac{1}{\sqrt{d_1^2 + d_2^2 + \lambda_\pm^2}}, \] (32)

one may write the mixing matrix as

\[ U_\nu^b = \begin{pmatrix} N_+ \lambda_+ & N_+ d_1 & N_+ d_2 \\ N_- \lambda_- & N_- d_1 & N_- d_2 \\ 0 & -\sqrt{d_1^2 + d_2^2} & \sqrt{d_1^2 + d_2^2} \end{pmatrix}. \] (33)

This matrix gives

\[ U_\nu U_\nu^{bT} = \text{diag}(\lambda_+, \lambda_-). \] (34)

If one neglects \( s_1 \), i.e. \( d \gg s_1 \), the non-zero eigenvalues reduce to \( \lambda_\pm = \pm \sqrt{d_1^2 + d_2^2} \). In this limit the mass matrix \( M_{\nu} \) displays the family symmetry \( L' = L_e - L_\mu - L_\tau \) discussed earlier. One may define

\[ c_{c}(s_c) = \frac{d_1(d_2)}{\sqrt{d_1^2 + d_2^2}}, \] (35)

and write the mixing matrix as

\[ U_\nu^c = \begin{pmatrix} 1 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -s_c & 0 & c_c \end{pmatrix}. \] (36)

Observe that \( U_\nu^c \) displays the exact bi-maximal form for \( d_1 = d_2 \).

### A. The PMNS Mixing Matrix

We now present the main results of our study, namely the PMNS mixing matrices \( U = U_I U_I^\dagger \) emerging from the hierarchies assumed in the charged lepton and neutrino mass matrices.

The results are presented in the table below, with the columns of this table containing the following information. The first column gives the hierarchy assumed in the charged lepton mass matrix. The second column contains the leading order rotation of the left-chiral charged leptons, \( U_L \). The third column contains the hierarchy assumed in the neutrino mass matrix. The leading order rotation for the neutrinos, \( U_\nu \), is presented in the fourth column and some important features of the resulting PMNS matrix are noted in the final column.

The features of a given mixing matrix pointed out in the final column fall into three categories.

- If a given PMNS matrix possesses an entry which is zero or near unity in a location which disagrees with the experimentally observed value this is pointed out to rule out the matrix.
- When a PMNS matrix is not ruled out but makes no specific predictions we point this out. These matrices are effectively too general to produce any distinct signature of the horizontal symmetry.
- Features of a given PMNS matrix which agree well with experiment are also pointed out. These include \( U_{e3} = 0 \) and predicted non-zero mixing angles.

When a rotation appears for the first time in the table its form is explicitly shown. We use distinct labels for the mixing angles in the different cases. Many of these angles are not explicitly shown in the text, however we wish to make it clear that these angles are in general distinct. The angles not shown correspond to less interesting scenarios and should their exact form be required they may readily be determined.

As noted earlier, the structure of the charged lepton rotations \( U_L \) and \( U_I \) are identical, meaning that the PMNS matrices which depend on either \( U_L \) or \( U_I \) have the same structure. We thus combine these cases together in the table found below.
| Hierarchy In $M_l$ | Charged Lepton Mixing $U_l^A$ | Hierarchy In $M_\nu$ | Neutrino Mixing $U_\nu^{\dagger}$ | Comments on $U = U_l U_\nu^{\dagger}$ |
|-------------------|--------------------------------|---------------------|--------------------------------|---------------------------------|
| $S_2 \gg T, S$    | $U_l^A = \begin{pmatrix} 0 & c_A & -s_A \\ 0 & s_A & c_A \\ 1 & 0 & 0 \end{pmatrix}$ | $t \gg s, \ t \gg d$ | $U_\nu^{\dagger} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_a & -s_a \\ 0 & s_a & c_a \end{pmatrix}$ | $U_{\tau 2} = U_{\tau 3} = U_{e 1} = U_{\mu 1} = 0$ |
| $S_2 \gg T, S$    | $U_l^A$                          | $s \gg t$           | $U_\nu^{\dagger} = \begin{pmatrix} 0 & 0 & 1 \\ c_a & s_a & 0 \\ -s_a & c_a & 0 \end{pmatrix}$ | only $\theta_{12} \neq 0$, $\theta_{12}$ remains general |
| $S_2 \gg T, S$    | $U_l^A$                          | $d \gg s, \ d \gg t$| $U_\nu^{\dagger} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ s_2 & c_2 & -s_c \\ -s_2 & c_2 & c_c \end{pmatrix}$ | $U_{\tau 3} = 0$ |
| $S_2 \gg T, S$    | $U_l^A$                          | $s \gg d$           | $U_\nu^{\dagger} = \begin{pmatrix} 0 & \frac{-\sqrt{d_1^2 + d_2^2}}{s_1} & 1 \\ -s_c & s_c & \frac{d_1}{s_1} \\ c_c & s_c & \frac{d_2}{s_1} \end{pmatrix}$ | $U_{\tau 1} = 0$ |
| $T \gg S, S_2, \ T, S \gg S_2$ or $T \gg D$ | $U_l^B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_B & -s_B \\ 0 & s_B & c_B \end{pmatrix}$ | $t \gg s, \ t \gg d$ | $U_\nu^{\dagger}$ | only $\theta_{23} \neq 0$, $\theta_{23}$ remains general |
| $T \gg S, S_2, \ T, S \gg S_2$ or $T \gg D$ | $U_l^F = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_F & -s_F \\ 0 & s_F & c_F \end{pmatrix}$ | $s \gg t$           | $U_\nu^{\dagger}$ | $U_{e 3} = 1$ |
| $T \gg S, S_2, \ T, S \gg S_2$ or $T \gg D$ | $U_l^B$                          | $d \gg s, \ d \gg t$| $U_\nu^{\dagger}$ | $U_{e 3} = 0$ $\tan \theta_{12} = 1$ |
| $T \gg S, S_2, \ T, S \gg S_2$ or $T \gg D$ | $U_l^F$                          | $s \gg d$           | $U_\nu^{\dagger}$ | $U_{e 3} = 1$ |
| Hierarchy In $M_l$ | Charged Lepton Mixing $U_l$ | Hierarchy In $M_\nu$ | Neutrino Mixing $U_\nu^\dagger$ | Comments on $U = U_l U_\nu^\dagger$ |
|-------------------|--------------------------|----------------------|----------------------|-------------------------------|
| $D \gg S$ or $D \gg T$, with $D_1^2 + D_2^2 \gg D_3^2 + D_4^2$ | $U_l^D = \begin{pmatrix} 0 & -s_D & c_D \\ 1 & 0 & 0 \\ 0 & c_D & s_D \end{pmatrix}$ | $t \gg s$, $t \gg d$ | $U_\nu^a\dagger$ | $U_{\tau 1} = U_{\mu 2} = U_{\mu 3} = U_{\tau 1} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_1^2 + D_2^2 \gg D_3^2 + D_4^2$ | $U_l^D$ | $s \gg t$ | $U_\nu^o\dagger$ | $U_{\mu 1} = U_{\mu 2} = U_{e 3} = U_{\tau 3} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_1^2 + D_2^2 \gg D_3^2 + D_4^2$ | $U_l^D$ | $d \gg s$, $d \gg t$ | $U_\nu^e\dagger$ | $U_{\mu 3} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_1^2 + D_2^2 \gg D_3^2 + D_4^2$ | $U_l^D$ | $s \gg d$ | $U_\nu^d\dagger$ | $U_{\mu 1} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_2^3 + D_4^3 \gg D_1^2 + D_2^2$ | $U_l^D$ | $t \gg s$, $t \gg d$ | $U_\nu^a\dagger$ | $U_{\tau 1} = U_{\mu 1} = U_{\tau 2} = U_{\tau 3} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_2^3 + D_4^3 \gg D_1^2 + D_2^2$ | $U_l^D$ | $s \gg t$ | $U_\nu^o\dagger$ | only $\theta_{12} \neq 0$, $\theta_{12}$ remains general |
| $D \gg S$ or $D \gg T$, with $D_2^3 + D_4^3 \gg D_1^2 + D_2^2$ | $U_l^D$ | $d \gg s$, $d \gg t$ | $U_\nu^e\dagger$ | $U_{\tau 3} = 0$ |
| $D \gg S$ or $D \gg T$, with $D_2^3 + D_4^3 \gg D_1^2 + D_2^2$ | $U_l^D$ | $s \gg d$ | $U_\nu^d\dagger$ | $U_{\tau 1} = 0$ |
To discuss the PMNS matrices constructed in the above table we define $U^X y = U^X U^y$. Of the sixteen matrices in the table one may discount twelve due to the presence of leading order zero entries in undesirable locations. Two of the remaining PMNS matrices, $U^{Aa}$ and $U^{Ea}$, predict only $\theta_{12} \neq 0$ and offer no insight into what the value of $\theta_{12}$ should be. Evidently, it is not desirable to consider the near maximal value of $\theta_{23}$ observed experimentally as the result of a perturbative correction to these matrices.

The matrices $U^{F a}$ and $U^{B a}$ contain $\theta_{23}$ as the only non-zero mixing angle. It is possible to construct realistic PMNS matrices as perturbations upon their existing structures. However, these matrices make no prediction as to what value $\theta_{23}$ should take and in the absence of an explicit model that generates VEV hierarchies amongst the VEV’s $t_{123} \text{ or } T_{123}$ they have little predictive power.

The matrices $U^{F c}$ and $U^{B c}$ prove to be the most interesting. They possess the same leading order structure, each containing a zero in the $e3 \rho$ position. The neutrino mixing matrix $U^\nu$ results from a mass matrix of the form

$$M_\nu = \begin{pmatrix} 0 & d_1 & d_2 \\ d_1 & 0 & 0 \\ d_2 & 0 & 0 \end{pmatrix},$$  \hspace{1cm} (37)

This displays the $L' = L_e - L_\mu - L_\tau$ symmetry, leading to an inverted hierarchy with $\Delta m^2_{12} = 0$. Perturbations are required to produce a splitting of order $\Delta m^2_{12} \sim 10^{-5}$ eV$^2$ and a non-maximal solar mixing angle. These perturbations may come from the charged lepton mass matrix or the neutrino mass matrix.

Consider first the charged lepton sector. The matrices $U^{F c}$ and $U^{B c}$ occur when the triplet scalar entries dominate the charged lepton mass matrix,

$$M_l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & T_2 & T_1 \\ 0 & T_3 & -T_2 \end{pmatrix},$$  \hspace{1cm} (38)

If the singlet entries are included one obtains

$$M_l = \begin{pmatrix} S_2 & 0 & 0 \\ 0 & S + T_2 & T_1 \\ 0 & T_3 & S - T_2 \end{pmatrix},$$  \hspace{1cm} (39)

so that $m_e = S_2$. This does not alter the solar mixing angle. If one instead includes the doublet entries in $M_l$,

$$M_l = \begin{pmatrix} 0 & D_3 & D_4 \\ D_1 & T_2 & T_1 \\ D_2 & T_3 & -T_2 \end{pmatrix},$$  \hspace{1cm} (40)

one obtains $m_e \sim D$. A correction of order $1^\circ$ to the solar mixing angle $\theta_{12}$ results, which is much too small to reach the experimentally favoured value of $\theta_{12} \sim 34^\circ$ [41].

One can consider the addition of both the singlet and doublet entries to the charged lepton mass matrix. However the electron mass develops a dependence on both $D$ and $S$ and the mixing angles emerging from the charged lepton sector remain too small under our assumed hierarchies. If $d_1 \sim d_2$ the neutrino mixing matrix has the bi-maximal form. A previous work has studied the forms of the charged lepton mixing matrix which are compatible with the experimentally observed PMNS matrix values when one assumes bi-maximal neutrino mixing [41]. The failure of the charged lepton mass matrices to adequately perturb the bi-maximal form of the neutrino mixing matrix in the present analysis reflects the disagreement between the forms of $M_l$, encompassed by the present study and those obtained in [41].

We now consider the addition of perturbations to the neutrino mass matrix. One can readily show that the addition of only $s_1$ to $M_\nu$ does not permit realistic values for $\Delta m^2_{12}$ and $\theta_{12}$ simultaneously. We shall consider the case where the singlet and triplet entries are included in the neutrino mass matrix. We are interested in the minimum additional number of scalar multiplets required to produce a realistic neutrino spectrum. However the case where only the triplet entries are included will readily be revealed in the appropriate limit of this more general case. We shall work in the basis where the charged lepton mass matrix has been diagonalized by the matrix $U^F$. We parameterise the neutrino mass matrix as

$$M_\nu = m_0 \begin{pmatrix} 0 & c & 0 \\ c & 0 & 0 \\ 0 & 0 & -\sqrt{\frac{w}{\sqrt{2}}} \end{pmatrix} + m_0 \begin{pmatrix} -w & 0 & 0 \\ 0 & -\sqrt{\frac{w}{\sqrt{2}}} & 0 \\ 0 & 0 & \frac{w}{\sqrt{2}} \end{pmatrix} = m_0 \{M_0 + M_1\},$$  \hspace{1cm} (41)

where $c = \cos \theta_{23}$ and $s = \sin \theta_{23}$ will turn out to be the cosine and sine of the atmospheric mixing angle. The mass scale of the eigenvalues is set by $m_0 \sim d$ and the entries in $M_l$ labelled $x, y$ and $z$ are of order $t/m_0$ whilst $w = s_1/m_0$. To first order in the small parameters $x, y, z$ and $w$ the ratio of mass squared differences is

$$\frac{\Delta m^2_{12}}{\Delta m^2_{23}} \approx \frac{2(2\kappa - w)}{1 - (2\kappa - w)},$$  \hspace{1cm} (42)

where we have introduced

$$\kappa = \frac{1}{2}(s^2 z - c^2 x) - \frac{y}{2\sqrt{2}} \sin 2\theta_{23},$$  \hspace{1cm} (43)

and it will prove useful to define

$$\xi = \frac{1}{2\sqrt{2}}(x + z) \sin 2\theta_{23} - \frac{y}{2} \cos 2\theta_{23}.$$  \hspace{1cm} (44)

The first order mixing matrix takes the form
\[ U = \begin{pmatrix}
\frac{1}{\sqrt{2}} + f & \frac{1}{\sqrt{2}} - f \\
-\frac{1}{\sqrt{2}} + cf - sk & \frac{1}{\sqrt{2}} + cf - sk \\
\frac{1}{\sqrt{2}} - sf - ck & \frac{1}{\sqrt{2}} - sf - ck
\end{pmatrix} \sqrt{2\xi}, \quad (45) \]

where
\[ f = \frac{1}{4\sqrt{2}}(2\kappa + w). \quad (46) \]

The neutrino mixing angles are
\[ \tan\theta_{13} \approx \sqrt{2}\xi, \quad (47) \]
\[ \tan\theta_{23} \approx \frac{s}{c}, \quad (48) \]
\[ \tan\theta_{12} \approx 1 - \frac{1}{2}(2\kappa + w). \quad (49) \]

Consider first the case where no singlet entry is present in the neutrino mass matrix, namely the limit \( w \to 0 \) in \( M_1 \). One then has
\[ \frac{\Delta m_{12}^2}{\Delta m_{23}^2} \approx \frac{2\kappa}{1 - 2\kappa}, \quad (50) \]

and
\[ \tan\theta_{12} \approx 1 + \kappa. \quad (51) \]

The current allowed \( 3\sigma \) ranges for the mass squared differences are [42]

\[ 7.1 \leq \Delta m_{12}^2 / (10^{-5} eV^2) \leq 8.9, \]
\[ 1.4 \leq \Delta m_{23}^2 / (10^{-3} eV^2) \leq 3.3, \quad (52) \]

and the mixing angles lie in the ranges
\[ 0.24 \leq \sin^2\theta_{12} \leq 0.4, \]
\[ 0.34 \leq \sin^2\theta_{23} \leq 0.68, \]
\[ \sin^2\theta_{13} \leq 0.047. \quad (53) \]

Equation (50) requires the single parameter \( \kappa \) to be small (of order \( 10^{-5} \)), thereby rendering the required deviation from maximal solar mixing unrealisable in concordance with equation (51).

When both the singlet and triplet entries are included as perturbations realistic values for both the ratio of mass squared differences [42] and the solar mixing angle [49] can be obtained. This results from the fact that the solar mixing angle depends on the linear combination of parameters \( (2\kappa + w) \) in [49] whilst the ratio of mass squared differences in [42] depends on the linearly independent combination \( (2\kappa - w) \). Assuming a maximal value for \( \theta_{23} \) the experimental range of \( \theta_{12} \) values are obtained for \( w \) and \( \kappa \) in the approximate ranges \( |w| \approx [0.18, 0.44] \) and \( |\kappa| \approx [0.09, 0.22] \).

This result is similar to that obtained in the work by Leontaris, Rizos and Psallidas in reference [29] (and more recently [43]). In that work lepton mass matrices with leading order structures identical to [37] and [39] were obtained by augmenting the standard model with an anomalous \( U(1) \) symmetry.

As the spectrum is inverted, with \( m_3 = 0 \) eV to zeroth order in the small parameters, one has
\[ m_0 \approx \sqrt{\Delta m_{23}^2}, \]

giving the \( 3\sigma \) range
\[ m_0 / (10^{-2} \text{eV}) \in [3.7, 5.7]. \quad (54) \]

The effective mass in neutrinoless double beta decay may be expressed as
\[ \langle \langle m \rangle \rangle = \sum_i U_{ei}^2 m_i \]
\[ = m_{0w}, \quad (55) \]

where \( i = 1, 2, 3 \) labels the neutrino mass eigenstates. Using the allowed range for \( w \) and [54] one obtains
\[ \langle \langle m \rangle \rangle / (10^{-2} \text{eV}) \in [0.7, 2.5], \quad (56) \]

which puts the effective neutrinoless double beta decay mass just below current experimental bounds (see eg [42]). Thus if the present framework is valid one is likely to observe neutrinoless double beta decay in the next generation of experiments, which will reach an accuracy of \( \langle \langle m \rangle \rangle \sim \text{few} \times 10^{-2} \text{eV} \) [44, 45]. The mixing matrix element \( U_{e3} = \sqrt{2\xi} \) is not uniquely determined in the present framework. Taking the atmospheric mixing angle to be maximal gives \( U_{e3} = (x + z)/2 \), with the small parameters \( x \) and \( z \) not sufficiently constrained to allow a unique prediction.

**B. Summary**

We have found that a realistic lepton spectrum and PMNS matrix are obtained when couplings to the scalars \( \chi \) and \( \Delta_2 \) dominate the charged lepton and neutrino mass matrices respectively. The required fine structure necessitates the inclusion of mass matrix entries resulting from couplings to \( \Delta_1 \) and \( \Delta_3 \) in the neutrino sector and either \( \phi \) or \( \Phi \) in the charged lepton sector. Thus a minimum of five (out of the possible six) scalar multiplets are necessary to reproduce the experimentally observed lepton sector within the present framework.

The neutrinos are required to display an inverted hierarchy, with the leading order neutrino mass matrix displaying the non-standard lepton number symmetry \( L' = L_e - L_\mu - L_\tau \). Should the neutrino mass spectrum turn out to be inverted the horizontal symmetry \( SU_H(2) \) may explain why nature displays the approximate symmetry \( L' \).
V. SCALARS AND HORIZONTAL GAUGE BOSONS

We wish to make a few remarks regarding the scalar content required for a realistic model and the mass scale of the horizontal gauge bosons. Though it is beyond the scope of the present work to construct and analyse a specific scalar potential, a comment on the scale of the VEV’s obtained by the $SU_L(2)$ triplet fields is in order.

It is known that $SU_L(2)$ triplet fields may acquire naturally light VEV’s if the scalar potential contains a term linear in the given field [49]. In the case of the SM augmented to include one $SU_L(2)$ triplet field, the field $\Delta$ acquires a VEV of order $\mu v^2/M_\Delta^2$, where $v$ denotes the VEV of the SM Higgs field $\Phi^0$. $\Delta$ is the mass of the field $\Delta$ and $\mu$ denotes the coefficient of the scalar potential term linear in $\Delta$, i.e. $\mu \Delta \Phi^0 \Phi^0 \subset V$, where $V$ is the scalar potential. Thus provided $\Delta$ is heavy enough its VEV will be suppressed relative to the electroweak scale.

Within the framework employed in the present study we have seen that a realistic neutrino sector requires three $SU_L(2)$ triplet fields, $\Delta_1$, $\Delta_2$ and $\Delta_3$, which form singlet, fundamental and triplet representations of $SU_H(2)$ respectively. Evidently we would like to ensure that the potential contains terms in these fields in order to allow them to develop VEV’s below the electroweak scale. The minimal scalar content required to produce a realistic charged lepton spectrum consists of the $SU_L(2)$ doublet fields $\phi$ and $\chi$, which form respectively singlet and triplet representations of $SU_H(2)$. With these five fields the potential will contain the terms:

\[ V \supset \Delta_1 (\mu_{11} \phi \phi + \mu_{13} \chi \chi) + \Delta_3 (\mu_{31} \phi \chi + \mu_{33} \chi \chi), \]

where the $\mu$’s are all dimension-full coupling constants. The above terms, being linear in $\Delta_1$ and $\Delta_3$, should allow these fields to naturally develop sub electroweak scale VEV’s. Without the inclusion of the field $\Phi^0$, which transforms as $(2,2)$ under $SU_L(2) \otimes SU_H(2)$, the potential does not contain a term linear in $\Delta_2$. The addition of $\Phi^0$ to the scalar spectrum results in additional potential terms, including

\[ \Delta_2 \mu_{22} \Phi^0 \chi, \]

which may allow $\Delta_2$ to obtain a VEV suppressed relative to the electroweak scale. Although a realistic charged lepton spectrum does not require the field $\Phi^0$, this field may be necessary to ensure the potential contains an appropriate term linear in $\Delta_2$.

In the work of KM the $SU_H(2)$ symmetry breaking scale is related to the light neutrino masses via the see-saw mechanism, namely $m_\nu \sim v^2/M_H$, where $M_H$ denotes the scale of horizontal symmetry breaking and $v$ is the electroweak scale. Assuming order one Yukawa couplings constrains $M_H$ to be roughly of order $10^{14}$ GeV. Consequently the horizontal gauge bosons become unobservably heavy.

In the present work, if an $SU_H(2)$ doublet of right-chiral neutrinos is included to remove the global anomaly, the see-saw contribution to the mass of the light neutrinos is required to be sub-dominant. Thus the lower bound on the scale of horizontal symmetry breaking becomes even more severe. Note that one only requires $SU_H(2)$ to be broken to $U(1)$ to generate heavy Majorana masses and we have no a priori reason to break the $U(1)$ subgroup at the scale $M_H$. However it may prove difficult to retain only mild hierarchies amongst the VEV’s of a given scalar multiplet with a non-zero horizontal charge (e.g. amongst $\chi_1 >, < \chi_2 >$ and $< \chi_3 >$) if this symmetry is broken at a vastly lower scale (see for example the discussion in [21]). It is beyond the scope of the present work to pursue this matter further.

The constraints on the horizontal symmetry breaking scale are much less severe if the horizontal symmetry communicates with a mirror sector. In this case the model need not include right chiral neutrinos and no see-saw induced connection between the mass of the light neutrinos and the scale of horizontal symmetry breaking arises.

The horizontal gauge bosons do not couple directly to quarks so that many of the usual bounds on additional neutral gauge bosons do not apply. The horizontal gauge bosons couple to the charged leptons as follows:

\[ -\mathcal{L} = g_H Z'_\mu \{ L_L \gamma^\mu U_1 L_L + \bar{L}_R \gamma^\mu V_1 L_R \} + \frac{g_H}{\sqrt{2}} Z'_\mu \{ \bar{L}_L \gamma^\mu U_2 L_L + \bar{L}_R \gamma^\mu V_2 L_R \} + \text{h.c.}, \]

where we use the label $Z'$ generically to denote a horizontal gauge boson and $g_H$ is the horizontal coupling constant. The horizontal charged lepton mixing matrices take the form

\[ U_1 = U_1 C_1 U_1^\dagger, \]
\[ U_2 = U_1 C_2 U_1^\dagger, \]
\[ V_1 = V_1 C_1 V_1^\dagger, \]
\[ V_2 = V_1 C_2 V_1^\dagger, \]

where $U_1$ and $V_1$ are the left- and right-chiral charged lepton mixing matrices respectively,

\[ U_1 M_l M_1^\dagger U_1^\dagger = \text{diag}(m_e^2, m_{\mu}^2, m_{\tau}^2), \]
\[ V_1^\dagger M_1 V_1 = \text{diag}(m_e^2, m_{\mu}^2, m_{\tau}^2), \]

and

\[ C_1 = \text{diag}(0, 1, -1), \]
\[ C_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}. \]

The matrices $C_{1,2}$ reflect the fact that there is a basis in which only two generations of leptons couple to the horizontal bosons and are proportional to linear combinations of the Pauli matrices.

When the triplet entries dominate the charged lepton mass matrix one has $U_1 = U_1 F$ and $V_1 = P' U_1^{F\dagger}$ to leading order, with

\[ P' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}. \]
In the absence of the field $\Phi$ the horizontal gauge bosons only couple to the muon and tauon generations of leptons. If the field $\Phi$ is included charged lepton mixing will couple the electron generation to the horizontal gauge bosons. Thus in principle the horizontal gauge bosons could be observed in $e^+e^-$ collisions. However the hierarchies assumed in the present study mean that the associated mixing angle will be of order $(m_e/m_\mu)^2$ or smaller. To see this, note that under the assumed hierarchies the horizontal mixing matrices will take the symbolic forms

$$U_1, V_1 \sim \begin{pmatrix} e^2 \epsilon \delta & e \delta \\ e \delta & 1 - e \delta \\ -e \delta & e \delta \end{pmatrix},$$ \hspace{1cm} (63)

and

$$U_2, V_2 \sim \begin{pmatrix} e^2 \epsilon \delta & e \delta \\ e \delta & \epsilon \delta^2 \delta^2 \\ -e \delta & e \delta \end{pmatrix},$$ \hspace{1cm} (64)

where $\epsilon$ denotes (different) elements of order $m_e/m_\mu$ or smaller, $\delta \sim c_F, s_F$ and $\delta^2 \sim c_F^2, s_F^2, c_F s_F$. Thus the coupling of $e^+e^-$ pairs to the horizontal gauge bosons are suppressed by a factor of $(m_e/m_\mu)^2 \sim 10^{-5}$. The flavour changing vertices coupling electrons and muons are suppressed by the larger factor of $(m_e/m_\mu)$. One can use the bound on the lepton number violating decay

$$\tau \rightarrow 2\mu + e,$$ \hspace{1cm} (65)

to constrain the coupling and mass of the horizontal bosons. If we follow \([9]\) and compare the branching ratio for this process to the SM decay

$$\tau \rightarrow \mu + 2\nu,$$ \hspace{1cm} (66)

we find \([50]\)

$$\frac{g_H^4}{M_{Z'}^2} \leq \frac{B(\tau \rightarrow 2\mu e)}{B(\tau \rightarrow \mu 2\nu)} \times \frac{m_\mu}{m_e} \times \frac{g_W^4}{M_W^4},$$ \hspace{1cm} (67)

where $g_W$ is the weak coupling constant, $M_{Z'}$ ($M_W$) is the horizontal ($W$) boson mass and we have taken $\delta \sim 1$. Using the current bound $B(\tau \rightarrow 2\mu e) < 1.5 \times 10^{-5}$ and $B(\tau \rightarrow \mu 2\nu) = 0.1736 \pm 0.0006$ \([52]\) one obtains the weak bound

$$\frac{g_H^4}{M_{Z'}^2} < 3.7 \times \frac{g_W^4}{M_W^4}.$$ \hspace{1cm} (68)

This demonstrates the difficulty in obtaining sensitive bounds on the horizontal bosons from processes involving electrons.

The horizontal gauge bosons will give rise to additional tauon decay modes of the type $\tau \rightarrow \mu + \text{invisible}$, namely

$$\tau \rightarrow \mu + Z' \rightarrow \mu + \nu_\mu + \nu_\tau,$$
$$\tau \rightarrow \mu + Z' \rightarrow \mu + \nu'_\mu + \nu'_\tau.$$ \hspace{1cm} (69)

Here $\nu'$ denotes mirror neutrinos, recalling that the horizontal gauge bosons couple to the mirror sector \([51]\). One may obtain bounds on the horizontal bosons by demanding that

$$\Gamma_{Extra}(\tau \rightarrow \mu + \text{inv}) \leq \Gamma_{Exp}(\tau \rightarrow \mu + \text{inv}) - \Gamma_{SM}(\tau \rightarrow \mu + \text{inv}),$$ \hspace{1cm} (70)

where $\Gamma_{Extra}(\tau \rightarrow \mu + \text{inv})$ is the width for the new decays \([69]\), $\Gamma_{Exp}(\tau \rightarrow \mu + \text{inv})$ is the experimentally measured width and $\Gamma_{SM}(\tau \rightarrow \mu + \text{inv})$ is the SM value. Using the measured values \([52]\),

$$B(\tau \rightarrow \mu + \text{inv}) = 0.1736,$$
$$\tau = 290.6 \times 10^{-15} \text{s},$$ \hspace{1cm} (71)

gives

$$\Gamma_{Exp}(\tau \rightarrow \mu + \text{inv}) = 3.93 \times 10^{-10} \text{MeV}.$$ \hspace{1cm} (72)

The SM value may be calculated as \([53]\)

$$\Gamma_{SM}(\tau \rightarrow \mu + \text{inv}) = \frac{G_F^2 m_\mu^5}{192\pi^3} F \left( \frac{m_\mu^2}{m_\tau^2} \right) \times r_{EW},$$ \hspace{1cm} (73)

where $G_F$ is the Fermi constant, $r_{EW} = 0.9960$ accounts for the electroweak propagator and radiative corrections \([54]\) and

$$F(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x.$$ \hspace{1cm} (74)

This gives

$$\Gamma_{SM}(\tau \rightarrow \mu + \text{inv}) = 3.90 \times 10^{-10} \text{MeV},$$ \hspace{1cm} (75)

leading to the upper limit

$$\Gamma_{Extra}(\tau \rightarrow \mu + \text{inv}) \leq 3.0 \times 10^{-12} \text{MeV}.$$ \hspace{1cm} (76)

This translates into the more restrictive bound

$$\frac{g_H^2}{M_{Z'}^2} \leq \frac{6 \times 10^{-2} g_{WS}^2}{M_W^2},$$ \hspace{1cm} (77)

which gives $M_{Z'} \geq 320 \text{ GeV}$ for $g_H = g_W$. This bound is low enough to allow the possible observation of horizontal gauge boson contributions to processes like $e^+e^- \rightarrow \mu^+\mu^-$ at the Next Linear Collider \([47]\). As the coupling of the horizontal bosons to $\mu^\pm$ is larger than the couplings to $e^\pm$, the horizontal bosons would create interesting phenomenology at a muon collider. Note also that the matrix $V_t$ appears in the
couplings between $Z'$ and the charged leptons. This allows one to experimentally reconstruct the matrix $V_l$.

VI. CONCLUSION

We have performed a systematic analysis of the PMNS matrices which arise when the three generations of leptons are assigned to the $2 \oplus 1$ representation of the horizontal symmetry $SU_H(2)$, and the neutrino mass matrix results from leptonic couplings to $SU_L(2)$ triplet scalar fields. It was assumed that hierarchies existed amongst lepton mass matrix elements which result from couplings to scalar fields with different charges under $SU_H(2)$. Of the sixteen candidate PMNS matrices which arose in our study it was found that only one was both predictive and possessed a leading order structure compatible with experimental observations. The relevant neutrino mass matrix displayed the symmetry $L_e - L_\mu - L_\tau$ to leading order and emerged when the contribution to the charged lepton mass matrix by a scalar forming a $(2,1,3)$ representation of $SU_L(2) \otimes U_Y(1) \otimes SU_H(2)$ dominated and the $(3,2,2)$ contributions to the neutrino mass matrix dominated. This PMNS matrix predicted maximal solar mixing, $U_{e3} = 0$ and left the atmospheric mixing angle unconstrained. It also required the neutrinos to display an inverted hierarchy. Perturbations to this leading order structure resulted from contributions to the neutrino mass matrix from additional scalar multiplets. Experimental data directly constrained the parameters which entered into the effective mass in neutrinoless double beta decay. This resulted in the prediction $<m> / (10^{-2} \text{eV}) \in [0.7, 2.5]$, which is just below current experimental bounds.

We also noted that the contribution of $SU_L(2)$ triplet scalar multiplets to the neutrino mass matrix can only dominate if the standard see-saw contribution is sub-dominant or not present. In the first case an $SU_H(2)$ doublet of right-chiral neutrinos may be included to remove the global anomaly as in the original work of KM. The sub-dominant nature of the see-saw contribution requires $SU_H(2)$ to be broken at an unobservably large scale. If there are no right-chiral neutrinos the global anomaly may be removed by allowing the horizontal symmetry to communicate with a mirror sector. In this case the scale of horizontal symmetry breaking may be much lower with hope of observing resonance behaviour of the horizontal gauge bosons at $e^+e^-$ colliders operating at TeV energies.

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[50] Note that the equations (41) and (42) in reference [9], obtained using the same procedure as us, contain the masses and coupling constants raised to the second power. These should be raised to the fourth power.

[51] The decay of $Z'$ into mirror neutrinos need not occur if the mirror symmetry is spontaneously broken. To ensure that oscillations of the ordinary neutrinos into mirror neutrinos are at most sub-dominant on solar system length scales, one requires either very small mass squared differences between the mirror parity eigenstates, or a spontaneously broken mirror symmetry to generate small ordinary-mirror mixing angles.

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