Democracy of Families

and

Neutrino Mass Matrix

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Abstract

On the basis of a seesaw-type mass matrix model for quarks and leptons, $M_f \simeq m_L M_F^{-1} m_R$, where $m_L \propto m_R$ are universal for $f = u, d, \nu$ and $e$ (up-quark-, down-quark-, neutrino- and charged lepton-sectors), and $M_F$ is given by $M_F = K(1 + 3 b_f X)$ ($1$ is a $3 \times 3$ unit matrix, $X$ is a democratic-type matrix and $b_f$ is a complex parameter which depends on $f$, neutrino mass spectrum and mixings are discussed. The model can provide an explanation why $m_t \gg m_b$, while $m_u \sim m_d$ by taking $b_u = -1/3$, at which the determinant of $M_F$ becomes zero. At $b_\nu = -1/2$, the model can provide a large $\nu_\mu$-$\nu_\tau$ mixing, $\sin^2 2 \theta_{23} \simeq 1$, with $m_{\nu_1} \ll m_{\nu_2} \simeq m_{\nu_3}$, which is favorable to the atmospheric and solar neutrino data.

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1. Basic standpoint
Considering the rapid increasing of the mass spectrum of quarks and leptons
as seen in Fig. 1, usually the horizontal degree of freedom is called “generations”.
The term “generations” suggests that there are hierarchical differences among those
generations. However, here, I would like to use a term “families” for the horizontal
degree of freedom.

My standpoint is as follows: All families take equivalent positions among
them, i.e., there is no family with a special position in the original state. This
does not always mean that the families should, for example, described by SU(3)
symmetry.

For example, if it is possible, I would like to describe these mass matrices
only in terms of “unit matrix and democratic-type matrix [1], i.e.,

\[
1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad X = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} .
\]

(1.1)
Unfortunately, the real mass spectrum (Fig. 1) seems to be more complicated to describe in terms of (1.1) only.

2. A unified quark and lepton mass matrix model

Before discussing my neutrino mass matrix, I would like to give a short review of a unified quark and lepton mass matrix model.

We consider vector-like heavy fermions \( F_i \) in addition to quarks and leptons \( f_i \) (\( f_i = u_i, d_i, e_i, \nu_i; \ i = 1, 2, 3 \)). These fermions belong to \( F_L = (1, 1) \), \( F_R = (1, 1) \), \( f_L = (2, 1) \), and \( f_R = (1, 2) \) of \( SU(2)_L \times SU(2)_R \), respectively. We assume the mass matrix form[2] for \((f, F)\)

\[
M = \begin{pmatrix} 0 & m_L \\ m_R & M_F \end{pmatrix},
\]

(2.1)

where we assume that the chiral symmetry breaking terms \( m_L \propto m_R \) have a universal structure for quarks and leptons and the heavy fermion mass term \( M_F \) has a structure of (unit matrix)+(a rank-one matrix) and \( M_F \) includes only one complex parameter which depends on quarks or leptons, and up- or down-, as we state later. As well-known, the \( 6 \times 6 \) mass matrix (2.1) leads to the so-called seesaw form

\[
M_f \simeq m_L M_F^{-1} m_R,
\]

(2.2)

for \( \text{Tr}M_F \gg \text{Tr}m_R, \text{Tr}m_L \).

For the origin of the mass matrices \( m_L \) and \( m_R \), I would like to consider a \( U(3) \)-family nonet Higgs potential scenario, which leads to an excellent charged lepton mass relation [3]

\[
m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2,
\]

(2.3)

However, such a multi-Higgs model, in general, induces flavor-changing neutral currents. The phenomenological study of the constraints on the Higgs boson masses has been given in Ref. [4] in the collaboration with Tanimoto: we have estimated that \( m_H \sim \) a several TeV from \( \Delta m(K_S-K_L) \), \( \cdots \), and rare decays \( K_L \rightarrow e^\pm + \mu^\mp, \cdots \).

However, since I have no sufficient time to review the scenario, I would like to skip the review from the present talk. Hereafter, apart from this scenario, we assume simply

\[
m_L \propto m_R \propto M_e^{1/2} \equiv \text{diag}(\sqrt{m_e}, \sqrt{m_\mu}, \sqrt{m_\tau}) .
\]

(2.4)
The most exciting feature of the present quark mass matrix is as follows: the model can naturally understand that why \( m_t \gg m_b \), while \( m_u \sim m_d \), without introducing such a parameter as it takes a large value in up-quark sector compared with that in down-quark sector.

The basic idea is as follows: we assume the following form [5] of \( M_F \),

\[
M_F \propto O_F = 1 + 3b_f e^{i\beta_f} X ,
\]

then the inverse matrix of \( O_F \) is given by

\[
O_F^{-1} = 1 + 3a_f e^{i\alpha_f} X ,
\]

with

\[
a_f e^{i\alpha_f} = -\frac{b_f e^{i\beta_f}}{1 + 3b_f e^{i\beta_f}} .
\]

Why \( m_t \gg m_b \) can be understood by taking \( b_u = -1/3 \) (\( \beta_u = 0 \)) because \( b_u \to -1/3 \) provides \( |a_u| \to \infty \), so that top-quark mass enhancement is caused (note that the seesaw form (2.2) is not valid any longer in the limit of \( b_u \to -1/3 \)). Why \( m_u \sim m_d \) is understood from the fact that democratic mass matrix makes only the third family heavy, i.e., the effects of \( |a_u| \to \infty \) affects only to \( m_t \).

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**Fig.2** Mass spectrum versus a parameter \( b_f \): solid and broken lines denote the cases of \( \beta_f = 0 \) and \( \beta_f = -20^\circ \), respectively.
The behavior of the mass spectrum versus $b_f e^{i \beta_f}$ is given in Fig. 2, where parameters $k$ and $K_f$ are defined by

$$M = \begin{pmatrix} 0 & m_L \\ m_R & M_F \end{pmatrix} = m_0 \begin{pmatrix} 0 & Z \\ kZ & K_f O_F \end{pmatrix}, \tag{2.8}$$

$$Z = \begin{pmatrix} z_1 & 0 & 0 \\ 0 & z_2 & 0 \\ 0 & 0 & z_3 \end{pmatrix}, \quad O_F = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + b_f e^{i \beta_f} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}. \tag{2.9}$$

Note that from the phenomenological point of view, it is not essential that $O_F = [(\text{unit matrix}) + (\text{democratic-type matrix})]$. Instead of (2.9), we may take

$$O_F = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + 3 b_f e^{i \beta_f} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2.10}$$

However, then, we must take the matrix $Z$ as the non-diagonal form

$$Z = \frac{1}{6} \begin{pmatrix} 3(z_2 + z_1) & -\sqrt{3}(z_2 - z_1) & -\sqrt{6}(z_2 - z_1) \\ -\sqrt{3}(z_2 - z_1) & 4z_3 + z_2 + z_1 & -\sqrt{2}(2z_3 - z_2 - z_1) \\ -\sqrt{6}(z_2 - z_1) & -\sqrt{2}(2z_3 - z_2 - z_1) & 2(z_3 + z_2 + z_1) \end{pmatrix}. \tag{2.11}$$

One may consider that the matrix forms (2.10) and (2.11) are favorable to model-building. However, I believe that the forms (2.9) are more promising.

Taking $b_u = -1/3$, $\beta_u = 0$ and $b_d = -1.0$, $\beta_d = -18^\circ$, but keeping $K_u = K_d$, we can provide not only reasonable quark mass ratios $m_u/m_c$, $m_c/m_t$, $m_d/m_s$ and $m_s/m_b$, but also $m_u/m_d$, $m_c/m_c$ and $m_t/m_t$, and, moreover, we can provide reasonable values of Kobayashi-Maskawa (KM) matrix parameters. For the details, please see a preprint Ref.[6] in the collaboration with Fusaoka.
3. Neutrino mass matrix with large $\nu_\mu$-$\nu_\tau$ mixing

So far, we have assumed the following mass terms:

\begin{align*}
\nu_L &= (2, 1, 3)_L^{Y=-1} \\
\nu_R &= (1, 2, 3)_R^{Y=-1} \\
\uparrow m_L & \quad \uparrow m_R \\
N_R &= (1, 1, 3)_R^{Y=0} & \leftrightarrow & N_L &= (1, 1, 3)_L^{Y=0} .
\end{align*}

Now, in order to understand why $m_\nu \ll m_\ell, m_q$, we must introduce a large Majorana mass term $M_M (\gg M_D)$ (hereafter, we denote the Dirac mass term $M_F$ for $F = N$ as $M_D$ in contrast to the Majorana mass matrix $M_M$).

Table I. Comparison between Model I and Model II

|                      | Model I                      | Model II                      |
|----------------------|------------------------------|------------------------------|
| $L$-$R$ Symmetric    | $N_L$ and $N_R$ acquire $M_M$ | $\nu_R$ acquires $M_M$       |
| $M = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2}m_L \\ 0 & 0 & \frac{1}{2}m_R^T & 0 \\ \frac{1}{2}m_L^T & 0 & M_D & M_D \end{pmatrix}$ | $M = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2}m_L \\ 0 & M_M & \frac{1}{2}m_R^T & 0 \\ 0 & \frac{1}{2}m_R & 0 & M_D \end{pmatrix}$ | $\begin{pmatrix} \frac{1}{2}m_L & 0 & M_D^T & 0 \end{pmatrix}$ |
| $M_{\nu L} \approx \left(\frac{1}{2}\right)^2 m_L M_M^{-1} m_L^T$ | $M_{\nu L} \approx \left(\frac{1}{2}\right)^4 m_L M_D^{-1} m_R M_M^{-1}$ $\times m_R^T (M_D^T)^{-1} m_L^T$ |
| Assume $M_M = \frac{K_M}{K_D} M_D$ | Assume $M_M = m_0 K_M 1$ |
| $M_{\nu L} \approx \frac{1}{4} m_0 Z O_F^{-1} Z$ | $M_{\nu L} \approx \frac{1}{16} k^2 m_0 K_M Z O_F^{-1} Z \cdot Z O_F^{-1} Z$ |

I would like to propose two models: Model I, in which the vector-like heavy fermions $N_L$ and $N_R$ acquire large Majorana masses $M_M$, respectively; Model II, in which the right-handed neutrinos $\nu_R$ acquire large Majorana masses $M_M$. In the model I, the chiral $SU(2)_R$ symmetry is broken by $m_R$, while, in the model...
II, it is broken by $M_M$ with an extremely large energy scale. The characteristics of the models are listed in Table I. The predicted values of the neutrino mixings are identical in the models I and II, although the predicted values of neutrino mass ratios are different from each other. Note that in the model I, the light “right-handed” Majorana neutrinos $\nu'_Ri$, which are originated from $\nu_Ri$, appear with masses $m(\nu'_Ri) \simeq k^2 m(\nu_Ri) \ (i = 1, 2, 3)$ (we suppose $k \geq 10$).

We show the typical cases of $b_\nu$ (for simplicity, we consider the case $\beta_\nu = 0$) for the model I.

[Case $b_\nu = -\frac{1}{3} + \varepsilon$]

$$m_{\nu 1} \simeq \frac{3 m_e m_0}{8 m_\tau K_M}, \quad m_{\nu 2} \simeq \frac{1}{2} \frac{m_\mu m_0}{m_\tau K_M}, \quad m_{\nu 3} \simeq \frac{1}{27 \sqrt{2} |\varepsilon| K_M},$$  \hspace{1cm} (3.3)

where $m_0 = \sqrt{3} m_t$ at $\mu = \Lambda_W = 175$ GeV.

$$U_{\nu L} \simeq \begin{pmatrix}
\frac{1}{\sqrt{2}} \sqrt{m_e/m_\mu} & -\frac{1}{2} \sqrt{m_e/m_\mu} & -\frac{1}{2} \sqrt{m_e/m_\tau} \\
\sqrt{m_e/m_\tau} & \frac{1}{\sqrt{2}} & -\sqrt{m_\mu/m_\tau} \\
\sqrt{m_\mu/m_\tau} & 1 & 1
\end{pmatrix}. \hspace{1cm} (3.4)$$

[Case $b_\nu = -1/2$]

$$m_{\nu 1} \simeq \frac{1}{2} \frac{m_e m_0}{m_\tau K_M}, \quad m_{\nu 2} \simeq m_{\nu 3} \simeq \frac{1}{4} \sqrt{m_\mu m_0 m_\tau K_M},$$  \hspace{1cm} (3.5)

$$U_{\nu L} \simeq \begin{pmatrix}
1 & -\sqrt{m_e/m_\mu} & -\sqrt{m_e/m_\tau} \\
\frac{1}{\sqrt{2}} \left( \sqrt{m_e/m_\mu} - \sqrt{m_e/m_\tau} \right) & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} \left( \sqrt{m_e/m_\mu} + \sqrt{m_e/m_\tau} \right) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{pmatrix}. \hspace{1cm} (3.6)$$

[Case $b_\nu = -1$]

$$m_{\nu 1} \simeq m_{\nu 2} \simeq \frac{1}{4} \sqrt{m_e m_\mu m_0 m_\tau K_M}, \quad m_{\nu 3} = \frac{1}{8} \frac{m_0}{K_M},$$  \hspace{1cm} (3.7)

$$U_{\nu L} \simeq \begin{pmatrix}
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \left( \sqrt{m_e/m_\mu} - \sqrt{m_e/m_\tau} \right) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \left( \sqrt{m_e/m_\mu} + \sqrt{m_e/m_\tau} \right) \\
-\sqrt{m_e/m_\tau} & -\sqrt{m_\mu/m_\tau} & 1
\end{pmatrix}. \hspace{1cm} (3.8)$$
The $b_\nu$-dependency of the mass spectrum of the light neutrinos, $(m_{\nu 1}, m_{\nu 2}, m_{\nu 3})$, is similar to that in Fig.2. The $b_\nu$-dependency of the neutrino mixing matrix $U_{ij}$ is given in Fig.3.

**Recent atmospheric neutrino data from the Kamiokande [7]** have suggested that the $\nu_\mu$-$\nu_X$ mixing ($X = e$ or $\tau$) is caused maximally, i.e., $\sin^2 2\theta \simeq 1$, with $\Delta m^2 \sim 10^{-2}$ eV. On the other hand, solar neutrino data [8] have suggested that $\sin^2 2\theta \simeq 7 \times 10^{-3}$ and $\Delta m^2 \simeq 6 \times 10^{-6}$ eV$^2$. We consider that the atmospheric neutrino data show $\nu_\mu$-$\nu_\tau$ mixing, while the solar neutrino data show $\nu_e$-$\nu_\mu$ mixing, so that we interests in the case of $b_\nu \simeq -1/2$, which provides $\sin^2 2\theta_{23} \sim 1$ with $m_{\nu 1} \ll m_{\nu 2} \simeq m_{\nu 3}$.

Although, by taking $b_\nu \simeq -1/2$, we can get $\sin^2 2\theta_{e\mu} \simeq 7 \times 10^{-3}$ and $\sin^2 2\theta_{\mu\tau} \sim 1$, in the model I, we cannot explain the experimental fact $\Delta m^2_{32}/\Delta m^2_{21} \sim 10^3$, because $m_{\nu 2}$ and $m_{\nu 3}$ are highly degenerated at $b_\nu \simeq -1/2$ (at most, $\Delta m^2_{32}/\Delta m^2_{21} \sim 10^2$ at $b_\nu \simeq -0.4$). The situation cannot improved even if we consider $\beta_\nu \neq 0$.

In the model II, if we take, for example, $b_\nu = -0.41$, we can get the predictions $\sin^2 2\theta_{12} = 6.8 \times 10^{-3}$, $\Delta m^2_{21} \equiv 6 \times 10^{-6}$ eV$^2$, $\sin^2 2\theta_{23} = 0.58$, $\Delta m^2_{32} = 0.99 \times 10^{-2}$ eV$^2$, $m_{\nu 1} = 2.4 \times 10^{-8}$ eV, $m_{\nu 2} = 2.5 \times 10^{-3}$ eV, $m_{\nu 3} = 0.10$ eV, where $\Delta m^2_{21} = 6 \times 10^{-6}$ eV$^2$ has been taken as an input value in order to fix the free parameter $K_M$. Similarly, the case of $b_\nu = -0.5$ with $\beta_\nu \simeq 10^\circ$ can give a simultaneous
explanation of the atmospheric and solar neutrino data.

Also note that the case $b_\nu = -0.5$ with $\beta_\nu = 0$ can give a rough explanation of the atmospheric and LSND neutrino data (the LSND data [9] have suggested that $\sin^2 2\theta_{12} \simeq 3 \times 10^{-3}$ and $\Delta m^2_{21} \simeq 6$ eV$^2$), because the case predicts that $\sin^2 2\theta_{12} = 7.7 \times 10^{-3}$, $\Delta m^2_{21} = 1.7$ eV$^2$, $\sin^2 2\theta_{23} = 0.99 \times 10^{-2}$, $\Delta m^2_{32} \equiv 1.6 \times 10^{-2}$ eV, $m_{\nu_1} = 1.7 \times 10^{-4}$ eV, $m_{\nu_2} = 1.3$ eV, $m_{\nu_3} = 1.3$ eV. If this picture is correct, the mass matrix in the lepton sector must rigorously real, because the case $\beta_\nu \neq 0$ makes the mass degeneration between $\nu_2$ and $\nu_3$ mild.

4. Summary

As an extension of a unified quark and lepton mass matrix (2.8) with (2.9), neutrino masses and their mixings have investigated. When we take $b_e = 0$, reasonable values of up- and down-quark mass ratios and KM matrix parameters are obtained by taking ($b_u = -1/3$, $\beta_u = 0$) and ($b_d = -1$, $\beta_d \simeq 18^\circ$), and with keeping $K_u = K_d$.

For neutrino mass matrix, we have proposed two models: In Model I, $N_L$ and $N_R$ acquire large Majorana masses $M_M (\propto M_N)$, so that SU(3)$_{\text{family}}$ is badly broken by the energy scale of $M_M$; In Model II, $\nu_R$ acquire large Majorana masses $M_M \propto 1$, so that SU(2)$_{\text{R}}$ is badly broken by the energy scale of $M_M$. In the both models, especially, the case $b_\nu \simeq -1/2$ is interesting, because the case provides a maximal mixing $\sin^2 2\theta_{23} \simeq 1$ together with $m_{\nu_2} \simeq m_{\nu_3}$. Phenomenologically, Model II is favorable to the atmospheric and solar neutrino data.

In the present stage, why nature choose $b_\nu \simeq -1/2$, $b_e = 0$, $b_u = -1/3$ and $b_d \simeq -1$ is an open question. The phenomenological success of the present unified mass matrix form (2.8) with (2.9) should be taken seriously, and a more plausible model-building must be investigated urgently.

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