Lepton Flavor Violation as a Probe of Quark-Lepton Unification

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Abstract

The recent measurements of the solar neutrino mixing angle $\theta_{\text{sol}}$ and the Cabibbo mixing angle $\theta_{C}$ reveal a surprising relation, $\theta_{\text{sol}} + \theta_{C} \simeq \frac{\pi}{4}$. Interpreting this empirical relation as a support of the quark-lepton unification, we find that the PMNS mixing matrix can be decomposed into a CKM-like matrix and maximal mixing matrices, which can give profound implications on the quark-lepton unification. We explore a possibility to probe the implication of quark-lepton unification by considering the relative sizes of branching ratios for the lepton flavor violating radiative decay processes, $l_i \to l_j \gamma$, in the context of the supersymmetric standard model with heavy right-handed Majorana neutrinos.

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Neutrino studies will enter a new era when the MINOS experiment starts firing a neutrino beam toward the Soudan mine in March 2005. Until now, while the atmospheric neutrino deficit still points toward a maximal mixing between the tau and muon neutrinos, however the solar neutrino problem favors a not-so-maximal mixing between the electron and muon neutrinos. Surprisingly, it has recently been noted that the solar neutrino mixing angle $\theta_{\text{sol}}$ required for a solution of the solar neutrino problem and the Cabibbo angle $\theta_{C}$ reveal a striking relation \[\theta_{\text{sol}} + \theta_{C} \simeq \frac{\pi}{4},\] which is satisfied by the experimental results within a few percent accuracy $\theta_{\text{sol}} + \theta_{C} = 45.4^\circ \pm 1.7^\circ$ \[2, 3, 4\]. This quark-lepton complementarity (QLC) relation (1) has been simply interpreted as an evidence for certain quark-lepton symmetry or quark-lepton unification as shown in Refs. \[1, 5, 6, 7\].

To effectively describe the deviation from maximal mixing of solar neutrino as well as a small mixing element $U_{e3}$ and possible deviation from maximal mixing of atmospheric neutrino, three possible combinations of maximal mixing and a certain mixing matrix $U(\lambda)$ parameterized in terms of a small parameter $\lambda \sim \sin \theta_{C}$ have been proposed as parametrization of $U_{\text{PMNS}}$ \[8, 9, 10, 11\]:

\[
\begin{align*}
(a) & \quad U^\dagger(\lambda)U_{\text{bimax}}, \\
(b) & \quad U_{\text{bimax}}U^\dagger(\lambda), \\
(c) & \quad U^{m}_{23}U^\dagger(\lambda)U^{m}_{12}.
\end{align*}
\]

Here $U_{\text{bimax}}$ corresponds to the bi-maximal lepton mixing matrix \[12\], and $U^{m}_{23}, U^{m}_{12}$ denote the rotation matrices with (2,3) and (1,2) maximal mixing, respectively. Even though the present data is not sufficient to determine which combination can give correct flavor structure in lepton sectors, it is very important to single them out because the QLC relation is strongly correlated to each combination differently. As extensively studied in \[5\], the QLC relation can be derived from the parametrization given above but up to some corrections. These corrections to the QLC relation can be compensated with renormalization effects \[7\].

In this Letter, we will show that among possible forms of $U(\lambda)$ which are consistent with the neutrino experimental results, the “CKM-like” form of $U(\lambda)$ has profound implication on the quark-lepton unification. Motivated by this observation, we will study the implication
of the parametrization composed of bi-maximal mixing and $U_{\text{CKM}}$ reflecting quark-lepton unification by considering the lepton flavor violating (LFV) decays particularly in the context of supersymmetric standard model (SSM). We also examine a possibility to differentiate the above combinations by considering the relative size of branching ratios of the radiative LFV decays, $Br(l_i \rightarrow l_j \gamma)$ ($i, j = e, \mu, \tau$). While the LFV processes have tiny rates in the minimal extensions of the standard model (SM) with heavy right-handed Majorana neutrinos, the supersymmetric extensions of the SM can lead to sizable effects on the LFV processes due to new sources of lepton flavor violation. As is well known, the LFV decays in SSM can be caused by the misalignment of lepton and slepton mass matrices \[13\] and the branching ratios of the LFV decays depend on the specific structure of the neutrino Dirac Yukawa matrix $Y_{\nu}$. Therefore, we expect that a specific structure of $Y_{\nu}$ reflecting quark-lepton unification can lead to distinctive predictions for the branching ratios of the LFV decays. However, the branching ratios of the LFV decays in SSM strongly depend on several parameters which make it difficult to probe the structure of $Y_{\nu}$. Instead of considering the branching ratios of each LFV process, we can rely on the relative size of $Br(l_i \rightarrow l_j \gamma)$ among the three different flavors, because the relative size is almost free from arbitrary supersymmetric parameters. These ratios of $Br(l_i \rightarrow l_j \gamma)$ can be useful to probe the structure of $Y_{\nu}$ with the help of the parametrization of $U_{\text{PMNS}}$ given in Eq. (2). In particular, we expect that a hierarchical structure of $Y_{\nu}$ predicted by quark-lepton unification may be responsible for the hierarchy of $Br(l_i \rightarrow l_j \gamma)$ if they are observed in the future experiments. In such a way, the quark-lepton unification could be tested from the determination of the relative size of the branching ratios in future experiments.

Let us begin by considering how the parametrization given by the forms of Eq. (2) can be realized in the framework of the quark-lepton unification. For our purpose, it is useful to work in a basis where the quark and lepton Yukawa matrices are related to each other by a certain symmetry. In general, the quark Yukawa matrices $Y_u, Y_d$ are given by

$$Y_u = U_u Y_u^\text{diag} V_u^\dagger, \quad Y_d = U_d Y_d^\text{diag} V_d^\dagger,$$

from which the observable CKM quark mixing matrix is described as $U_{\text{CKM}} = U_u^\dagger U_d$. For the lepton sector, we consider the following leptonic superpotential, which implements the seesaw mechanism:

$$W_{\text{lepton}} = Y_{\nu} \hat{\nu}_L \hat{H}_d + Y_{\nu} \hat{\nu}_L \hat{N}_L \hat{H}_d - \frac{1}{2} \hat{N}_L^c M_R \hat{N}_L^c, \quad (3)$$

where the family indices have been suppressed and $\hat{L}_j, j = e, \mu, \tau \equiv 1, 2, 3$, represent the
chiral super-multiplets of the \( SU(2)_L \) doublet lepton fields, \( \hat{N}^c_{jL}, \hat{\ell}^c_{jL} \) are the super-multiplet of the \( SU(2)_L \) singlet neutrino and charged lepton field, respectively. In the superpotential \( W_{\text{lepton}} \), \( M_R \) is the heavy Majorana neutrino mass matrix. \( Y_l \) and \( Y_\nu \) are the 3 \( \times \) 3 charged lepton and neutrino Dirac Yukawa matrices, respectively and can be parameterized as

\[
Y_l = U_l Y^\text{diag}_l V^\dagger_l, \quad Y_\nu = U_\nu Y^\text{diag}_\nu V^\dagger_\nu. \tag{4}
\]

We note that in the framework of the minimal unification and the symmetric basis where the quarks and leptons are interrelated, \( M_R \) is generally not diagonal. The light neutrino mass matrix can be generated through the seesaw mechanism after the breaking of the electroweak symmetry as

\[
M_\nu = \left( U_0 M^\text{diag}_\text{Dirac}_0 V^\dagger_0 \right) M^{-1}_R \left( V^*_0 M^\text{diag}_\text{Dirac}_0 U^T_0 \right), \tag{5}
\]

where \( M^\text{diag}_\text{Dirac} = Y_\nu v_u / \sqrt{2} \) with \( v_u = v \sin \beta \). We can then rewrite \( M_\nu \) as follows

\[
M_\nu = U_0 V_M M^\text{diag}_\nu V^T_M U^T_0, \tag{6}
\]

where \( V_M \) represents the diagonalizing matrix of

\[
M^\text{diag}_\text{Dirac} V^\dagger_0 M^{-1}_R V^*_0 M^\text{diag}_\text{Dirac}.
\]

Then, the observable PMNS mixing matrix can be written as

\[
U_{\text{PMNS}} = U_l^\dagger U_\nu = U_l^\dagger U_0 V_M. \tag{7}
\]

Now, let us consider how \( U_{\text{PMNS}} \) given by Eq. (7) can be related with \( U_{\text{CKM}} \) in the context of quark-lepton unification. The quark-lepton unification based on the minimal \( SU(5) \) leads to the following simple relations,

\[
Y_e = Y^T_d, \quad Y_u = Y^T_u. \tag{8}
\]

Then, we deduce that \( U_l = V^*_d \) from which

\[
U_{\text{PMNS}} = V^T_d U_0 V_M. \tag{9}
\]

As one can easily see, the contribution of \( U_{\text{CKM}} \) may appear in \( U_{\text{PMNS}} \) if we further assume that the Yukawa matrix of the up-type quark sector is related with that of Dirac-type
neutrinos such as $Y_\nu = Y_u$ which can be realized in some larger unified gauge group such as $SO(10)$. Then, the lepton flavor mixing matrix can be written as

$$U_{PMNS} = V_d^T U_d U_{CKM}^T V_M.$$  \hfill (10)

In addition, requiring symmetric form of the down-type quark Yukawa matrix, we obtain

$$U_{PMNS} = U_{CKM}^T V_M,$$  \hfill (11)

where the mixing matrix $V_M$ should have two almost maximal mixings so as to account for the solar and atmospheric neutrino oscillations. This expression for $U_{PMNS}$ corresponds to the parametrization given by Eq. (2a). On the other hand, in order to achieve the parametrization given by Eq. (2b), one should take $V_M$ to be identity matrix and the product of two matrix $V_d^T U_d$ in Eq. (10) should give bi-maximal mixing pattern. Since the left-handed rotation matrix $U_d$ for down type quark can be almost diagonal to leading order, $V_d^T$ should have almost bi-maximal mixing form, which can be achieved in the so-called lopsided form of Yukawa matrix. The case given by Eq. (2c) can also be achieved by taking $V_d^T \approx U_{23}^m$ and $V_M \approx U_{12}^m$ in Eq. (10). In such ways, $U_{PMNS}$ can be connected with $U_{CKM}$ in the framework of the quark-lepton unification.

Although the minimal quark-lepton unification can lead to an elegant relation between $U_{PMNS}$ and $U_{CKM}$ as shown above, it indicates undesirable mass relations between quarks and leptons at the GUT scale such as $m_{d_{\text{diag}}} = m_{l_{\text{diag}}}$. Thus, we need to modify the simple relations between quark and lepton Yukawa matrices so as to achieve desirable mass relations. From the well known empirical relation

$$|V_{us}| \simeq \sqrt{\frac{m_d}{m_s}} \simeq 3 \sqrt{\frac{m_e}{m_\mu}}.$$  \hfill (12)

it has been shown that the $U(\lambda)$ in Eq. (2) should have the CKM-like form but with the replacement of $\lambda$ with $\lambda/3$ as shown in Refs. [7, 14], which can be obtained by introducing the Higgs sector transforming under the representation $45$ of $SU(5)$ or $126$ of $SO(10)$ [15].

Now, let us consider how the relative ratio of $Br(l_i \rightarrow l_j \gamma)$ can be connected with the structure of the neutrino Dirac Yukawa matrix, which is constructed from the grand unification scenario above. It is well known that the RG running induces off-diagonal terms in the slepton mass matrix even for the case of universal slepton masses at GUT scale [16]:

$$m^2_{l_{ij}} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^r Y_\nu^r)_{ij} \log \frac{M_G}{M_X}.$$  \hfill (13)
where \( m_0, A_0 \) are universal soft scalar mass and soft trilinear \( A \) parameter, and \( Y'_\nu \) is defined in the basis where the charged lepton Yukawa matrix and the heavy Majorana mass matrix are real and diagonal. Here \( M_G \) and \( M_X \) denote the GUT scale and the characteristic scale of the right-handed neutrinos at which off-diagonal contributions are decoupled \( [16] \), respectively. Thus, one can expect that some specific form of \( Y'_\nu \) is crucial to estimate the sizes of LFV processes which are caused by non-diagonal slepton mass matrix. First of all, let us consider the parametrization (a). It follows from Eqs. (2-a,11) that

\[
Y'_\nu \equiv U_{\text{CKM}}^{-1} Y_D^D V_0^T V_R,
\]

(14)

where \( Y_D^D \) is diagonal neutrino Dirac Yukawa matrix and \( V_R \) is the rotation matrix of the heavy Majorana neutrino mass matrix \( M_R \) in Eq. (3). From Eq. (14), the term \((Y'_\nu Y'^T_\nu)\) becomes

\[
Y'_\nu Y'^T_\nu = U_{\text{CKM}}^{-1} (Y_D^D)^2 U_{\text{CKM}}.
\]

(15)

The induced off-diagonal terms in the slepton mass matrix can be a source of the lepton flavor violation in SSM and they can yield sizable contributions to LFV decays, \( l_i \to l_j \gamma \). The contribution to the branching ratios of the LFV decays due to the slepton mass term is roughly given by

\[
Br(l_i \to l_j \gamma) \simeq \frac{\alpha^3}{G_F^2} \tan^2 \beta \left| \frac{m_{l_{ij}}}{m_S} \right|^2,
\]

(16)

where \( m_S \) is a supersymmetric mass scale. Let us define \( Y_D^D \) in a hierarchical form expressed in terms of the power of \( \lambda \) :

\[
Y_D^D \equiv Y_3 \begin{pmatrix} \lambda^{n_1} \\ \lambda^{n_2} \\ 1 \end{pmatrix}.
\]

(17)

For the quark-lepton unification, \( Y_3 = m_t/v_u \) and the powers of \( \lambda \) are given by \( n_1 = 8, n_2 = 4 \) so as to be the same hierarchy of up-type quark sector at high energy scale.

The term \((Y'_\nu Y'^T_\nu)\) is roughly given to leading order as

\[
Y'_\nu Y'^T_\nu \sim \left( \frac{m_t}{v_u} \right)^2 \times \begin{pmatrix} \lambda^{2n_1} + \lambda^{2n_2 + 2} + \lambda^6 \\ \lambda^{2n_1 + 1} - \lambda^{2n_2 + 1} - \lambda^5 \\ \lambda^{2n_1 + 1} - \lambda^{2n_2 + 1} - \lambda^5 \\ \lambda^{2n_1 + 2} + \lambda^{2n_2} + \lambda^4 - \lambda^2 \\ \lambda^3 - \lambda^2 \\ 1 \end{pmatrix}.
\]

(18)
Inserting this into Eq. (16), we can estimate how large $Br(l_i \rightarrow l_j \gamma)$ could be by fixing the parameters $m_S$ and $M_X$. Instead of considering the values of $Br(l_i \rightarrow l_j \gamma)$, we focus on the ratio of $Br(l_i \rightarrow l_j \gamma)$. The ratio of $Br(l_i \rightarrow l_j \gamma)$ only depends on $Y'_\nu Y'^\dagger_\nu$, and thus from Eqs. (13, 16, 18), we can simply obtain the ratio:

$$Br(\mu \rightarrow e\gamma) : Br(\tau \rightarrow e\gamma) : Br(\tau \rightarrow \mu\gamma) \simeq (-\lambda^{2n_1-1} + \lambda^{2n_2-1} + \lambda^3)^2 : \lambda^2 : 1. \quad (19)$$

When $Y'^D_\nu$ is the same as $Y'^D_u$ due to the quark-lepton unification, we predict that the ratio given in Eq. (19) should be $(\lambda^6 : \lambda^2 : 1)$. But, we note that this ratio may not necessarily indicate quark-lepton unification just considered because we can obtain the same ratio in the limit of large values of $n_1, n_2$. However, if the ratio of $Br(l_i \rightarrow l_j \gamma)$ is measured to be inconsistent with the prediction of the ratio given above, it may indicate $Y'^D_\nu \neq Y'^D_u$.

For the case of realistic quark-lepton unification satisfying Eq. (12), the terms $(Y'_\nu Y'^\dagger_\nu)_{i,j}$ for $(i, j) = (2, 1), (3, 1), (3, 2)$ are roughly given as

$$(Y'_\nu Y'^\dagger_\nu)_{21} \simeq \frac{\lambda^5}{6} + \frac{\lambda^{1+2n_1}}{3} - \frac{\lambda^{1+2n_2}}{3}$$

$$(Y'_\nu Y'^\dagger_\nu)_{31} \simeq \frac{\lambda^3}{6} - \frac{\lambda^{3+2n_1}}{2} + \frac{\lambda^{3+2n_2}}{3}$$

$$(Y'_\nu Y'^\dagger_\nu)_{32} \simeq \lambda^2 - \frac{\lambda^{4+2n_1}}{6} - \lambda^{2+2n_2}. \quad (20)$$

Then, the ratio of $Br(l_i \rightarrow l_j \gamma)$ among the three different flavors is

$$Br(\mu \rightarrow e\gamma) : Br(\tau \rightarrow e\gamma) : Br(\tau \rightarrow \mu\gamma) \simeq (\lambda^{2n_1} - \lambda^{2n_2} + \lambda^4)^2 : \lambda^4 : 1, \quad (21)$$

in order of magnitude estimation. For $n_1 = 8, n_2 = 4$, the ratio becomes $\lambda^8 : \lambda^4 : 1$. Therefore, we may confirm the validity or breaking of the quark-lepton unification through the measurements of the ratios of $Br(l_i \rightarrow l_j \gamma)$. As can be seen from Eq. (18), the important elements in $U_{\text{CKM}}$ which actually determine the hierarchy among $Br(l_i \rightarrow l_j \gamma)$ are $(U_{\text{CKM}})_{13}$ and $(U_{\text{CKM}})_{23}$. For more precise predictions of the relative branching ratios, it is urgently required to determine $(U_{\text{CKM}})_{13}$ and $(U_{\text{CKM}})_{23}$ experimentally with better accuracy. Note that the lepton mixing matrix given by Eq. (11) leads to a new QLC relation,

$$(U_{\text{PMNS}})_{e3} = [-\lambda + (U_{\text{CKM}})_{31}]/\sqrt{2}. \quad (22)$$
Therefore, we are led to further confirm or discard quark-lepton unification through the measurement of \((U_{\text{CKM}})_{31}\) and \((U_{\text{PMNS}})_{3}\). Note that similar to the QLC relation between \(\theta_{\text{sol}}\) and \(\theta_{C}\), we can get another QLC relation between the mixing angle \(\theta_{\text{atm}}\) and \((\theta_{23})_{\text{CKM}}\),

\[
\theta_{\text{atm}} + (\theta_{23})_{\text{CKM}} \simeq \pi/4. \tag{23}
\]

Similar to the parametrization (2-a), we can easily estimate the relative ratios of \(Br(l_i \to l_j \gamma)\) for the parameterizations in (2-b) and (2-c). In these cases, the term \(Y'_{\nu}Y'^{\dagger}_{\nu}\) becomes

\[
Y'_{\nu}Y'^{\dagger}_{\nu} = \begin{cases} 
U_{\text{bimax}}U^{\dagger}_{\text{CKM}}(Y'_{\nu}D)^{2}U_{\text{CKM}}U^{\dagger}_{\text{bimax}} & (2-b), \\
U_{23}^{m}U^{\dagger}_{\text{CKM}}(Y'_{\nu}D)^{2}U_{\text{CKM}}U^{\dagger}_{23} & (2-c).
\end{cases} \tag{24}
\]

Imposing the hierarchy of \(Y'_{\nu}D\) given by Eq. (17), the relative ratios of \(Br(l_i \to l_j \gamma)\) become

\[
Br(\mu \to e\gamma) : Br(\tau \to e\gamma) : Br(\tau \to \mu\gamma) \\
\simeq \lambda^{4} : \lambda^{4} : 1 \quad (2-b), \quad \lambda^{6} : \lambda^{6} : 1 \quad (2-c). \tag{25}
\]

From the predictions (19,25), one can see that experimental determination of the relative ratios of \(Br(l_i \to l_j \gamma)\) can differentiate the parameterizations of the quark-lepton unification if the empirical QLC relations indeed indicate the quark-lepton unification.

We note that the RG-induced off-diagonal terms in the slepton mass matrix is more precisely given by

\[
m_{\tilde{l}_{ij}}^{2} \simeq -\frac{1}{8\pi^{2}}(3m_{0}^{2} + A_{0}^{2}) \left( Y'_{\nu_{ik}} \log \frac{M_{G}}{M_{R_{k}}} Y'^{\dagger}_{\nu_{kj}} \right). \tag{26}
\]

In this expression, we see that the prediction of \(Br(l_i \to l_j \gamma)\) depends on the hierarchy of the heavy Majorana neutrino mass eigenvalues \(M_{R_{k}}\). However, we note that the hierarchy is not arbitrary but derived from seesaw formulae if we fix a light neutrino mass \(m_{\nu_{1}}\) in our framework. According to our numerical estimation on the relative ratios of \(Br(l_i \to l_j \gamma)\) based on Eq. (26), the hierarchical patterns given in Eqs. (19,21,25) are almost kept, as long as \(m_{\nu_{1}} \geq 10^{-5} \text{ eV}\). This is due to the mild hierarchy of \(\log \frac{M_{G}}{M_{R_{k}}}\).

In summary, interpreting the surprising empirical relation, \(\theta_{\text{sol}} + \theta_{C} \simeq \frac{\pi}{4}\), as a support of the quark-lepton unification, we find that the PMNS mixing matrix can be parameterized by a CKM-like matrix and maximal mixing matrices in various ways. Each parametrization may imply very different fundamental flavor structure. We have shown that the various parameterizations of \(U_{\text{PMNS}}\) with regard to quark-lepton unification would give very different
and profound implication to the radiative leptonic decays, $l_i \rightarrow l_j \gamma$, in the context of SSM. Therefore, by measuring the relative size of the radiative decay branching ratios, we will be able to pin down the $U_{PMNS}$ parametrization, assuming the quark-lepton unification. There have been proposed experiments [18] to measure these radiative decays. The proposal in this Letter can soon be tested for the quark-lepton unification.

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