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Radiative Neutrino Masses and Quark and Lepton Unification Model[1]

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Abstract

Against to the conventional point of view that the radiative mass generation mechanism cannot be embedded into the framework of a SUSY GUT model, we conclude that the difficulty is not an inevitable trouble in the theory, and we demonstrate that model-building of such a SUSY GUT model without proton decay is, indeed, possible. We will give a general mass matrix form for the radiatively-induced neutrino masses. And also, some related topics on the mass matrix models are reviewed.

Contents

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1 Introduction: What is the problem?

One of the most challenging problems in contemporary physics is to give a unified understanding of the quarks and leptons, especially, of their masses and mixings. Although over two decades many mass matrix models have been proposed, there is yet not a unified quark and lepton mass matrix model which has a theoretically reliable base and can give phenomenologically successful predictions. In such the situation, the investigation of the origin of the neutrino masses can become a breakthrough in the unified understanding of the quarks and leptons: why the observed neutrinos have such tiny masses compared with other fundamental constituents (quarks and charged leptons)?

There are two antithetical ideas as a neutrino mass generation mechanism: One is so-called seesaw mass generation mechanism [1] which was proposed by Gell-Mann, Ramond and Slansky (1979) and independently by Yanagida (1979), and another one is the radiatively-induced mass generation mechanism which was first proposed by Zee (1980) [2]. In the former idea, the neutrinos acquire Dirac masses m_D of the same order as quark and charged lepton masses, and the smallness of the observed neutrino masses m_ν is explained by a seesaw-like mechanism

$$m_\nu = m_D M_R^{-1} m_D^T, \tag{1.1}$$

due to large Majorana masses M_R of the right-handed neutrinos ν_R. To the contrary, in the latter idea, there are no right-handed neutrinos, so that there are no Dirac mass terms, and the tiny Majorana neutrino masses are generated radiatively (see Fig. 1).

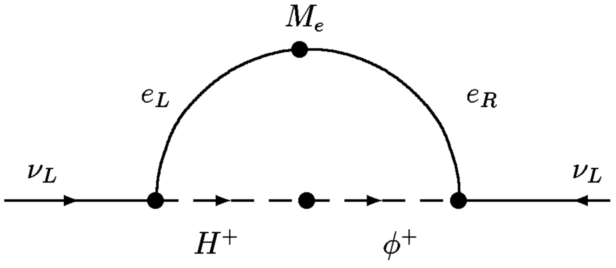

Fig. 1 Radiative mass generation in the Zee model, where ϕ^+ is a charged SU(2)$_L$ singlet scalar.

Currently, the former idea is influential, because it is hard to embed the latter idea into a grand unification theory (GUT). A supersymmetric (SUSY) model with R-parity violation can provide neutrino masses radiatively [3], but the model cannot be embedded into GUT, because the R-parity violating terms induce proton decay catastrophically [4]. For example, when we consider the following R-parity violation terms,

$$\begin{aligned} W_{\not R} &= \lambda_{ijk}(\overline{5}_L)_i^\alpha(\overline{5}_L)_j^\beta(10_L)_{\alpha\beta k} \\ &= \frac{1}{\sqrt{2}}\lambda_{ijk}\left\{\varepsilon_{abc}(d_R^c)_i^a(d_R^c)^b(u_R^c)_k^c - [(e_L)_i(\nu_L)_j - (\nu_L)_i(e_L)_j](e_R^c)_k \right. \\ & \left. -[(e_L)_i(d_R^c)_j^a - (d_R^c)_i^a(e_L)_j](u_L)_{ka} + [(\nu_L)_i(d_R^c)_j^a - (d_R^c)_i^a(\nu_L)_j](d_L)_{ka}\right\}, \end{aligned} \tag{1.2}$$

(SU(5) indices $\alpha, \beta = 1, 2, \cdots, 5$; SU(3) color indices a, b, c=1, 2, 3; flavor indices i, j, k=1, 2, 3) in an SU(5) GUT model, the tems $(e_L \nu_L - \nu_L e_L) e^c_R$ can contribute to the neutrino masses through the diagram given in Fig. 4 (Sec. 3). However, then, a rapid proton decay is inevitably induced by the terms $(\nu_L d^c_R - d^c_R \nu_L) d_L$ and $d^c_R d^c_R u_R$. Our interest is to investigate whether there is or not a SUSY GUT model in which the terms $(e_L \nu_L - \nu_L e_L) e^c_R$ are sizable, while the term $(\nu_L d^c_R - d^c_R \nu_L) d_L$ and $d^c_R d^c_R u_R$ are highly suppressed.

Our conclusion [5, 6, 7] is that the difficulty in the radiative mass generation in a framework of a SUSY GUT model is not an inevitable trouble in the theory. Indeed, we have demonstrated that the radiative mass generation without a rapid proton decay is able to embed into a SUSY GUT model. In Sec. 3, we will show a basic idea of the avoidance by giving a short review of our first model [5], where, in addition to the conventional matter fields $\overline{5}_L + 10_L$ of $\mathrm{SU}(5)_{GUT}$ and Higgs fields $\overline{H}_d + H_u$, there are additional Higgs fields $\overline{H}'_d + H'_u$. In Sec. 4, we will also review another SUSY SU(5) GUT model with additional matter fields $\overline{5}'_L + 5'_L$ [6, 7].

In Sec. 5, we will discuss three topics related to the unified description of the quark and lepton mass matrices. The first topic is discussed about an attempt of the unified description apart from the SUSY GUT framework. Here, we will demand the so-called "flavor 2 ↔ 3 symmetry", which was first introduced in order to give an explanation of the neutrino masses and mixings [8]. We will find that we can give a unified description of the quark and lepton mass matrices by applying the same matrix forms not only to the neutrino sector, but also to all fermion sectors.

In the subsection 5.2, we will give some points to notice in investigating mass matrix models based on flavor symmetries. Recently, many neutrino mass matrix models based on flavor symmetry, especially, on discrete symmetries, have been proposed. We will emphasize that it is important to check whether the same symmetry transformation can be applied not only to the neutrino fields $(\nu_{L1}, \nu_{L2}, \nu_{L3})$, but also to the charged lepton fields (e_{L1}, e_{L2}, e_{L3}), or not. We will point out that any flavor symmetry has to be completely broken at a high energy scale, or else, the mass eigenvalues degenerate or the flavor mixings are only caused at most between two families.

The third topic is about a shape of the unitary triangle, i.e. CP violation structure in the quark sector. In Sec. 5.3, we will stress that the investigation will provide a promising clue to the unified mass matrix models as well as investigation in the neutrino mass matrix phenomenology.

Finally, Sec. 6 will be devoted to the summary and concluding remarks.

2 Observed values of masses and mixings

Let us now review the present experimental status on the quark and lepton masses and their mixings. At the same time, for convenience of following discussions, we will give the definitions (notations and conventions) of the mass matrices and flavor mixing matrices.

First, we review the observed value of quark masses and their mixings prior to a review of the neutrino masses and mixings, since one of the purposes of the present research project is to search for a unification model of quarks and leptons although the main purpose is to investigate the origin of the neutrino masses.

The quark mass values (running quark masses) $m_q(\mu)$ depend on the energy scale μ. When we discuss a quark mass matrix model, we usually use the values of $m_q(\mu)$ at $\mu = m_Z$ (m_Z is the mass of the neutral weak boson Z: $m_Z = 91.2$ GeV), because the quark mixing matrix, the Cabibbo-Kobayashi-Maskawa (CKM) [9] matrix V is observed through the weak interactions. (Of course, for the model-builders, the values of $m_q(\mu)$ at the grand unification scale $\mu = M_{GUT}$ are also useful. However, the values $m_q(M_{GUT})$ are dependent on the unification model.) The systematical estimate of the quark masses has been given in 1982 by Gasser and Leutwyler [10]. The revised estimate has been given in 1998 by Fusaoka and the author [11]. The values at $\mu = m_Z$ are as follows:

$$
\begin{array}{lll}
m_u(m_Z) = 2.33^{+0.42}_{-0.45}\ \mathrm{MeV}, & m_c(m_Z) = 677^{+56}_{-61}\ \mathrm{MeV}, & m_t(m_Z) = 181 \pm 13\ \mathrm{GeV}, \\
m_d(m_Z) = 4.69^{+0.60}_{-0.66}\ \mathrm{MeV}, & m_s(m_Z) = 93.4^{+11.8}_{-13.0}\ \mathrm{MeV}, & m_b(m_Z) = 3.00 \pm 0.11\ \mathrm{GeV}, \\
m_e(m_Z) = 0.48684727\ \mathrm{MeV}, & m_\mu(m_Z) = 102.75138\ \mathrm{MeV}, & m_\tau(m_Z) = 1.74669\ \mathrm{GeV}, \\
\qquad \pm 0.00000033 & \qquad \pm 0.00033 & \qquad {}^{+0.00030}_{-0.00027}
\end{array}
\tag{2.1}
$$

where we have listed the charged lepton mass values at $\mu = m_Z$ in addition to the quark mass values.

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Fig. 2 Quark and charged lepton masses vs "families"
The plots have been taken by mass values given in (2.1).

However, in the estimate in 1998, the value $m_t = 180 \pm 12$ GeV which was quoted by Particle Data Group 1996 [12] has been used as the top quark mass from direct observations of top quark events. The recent value (Particle Data Group 2004) [13] is $m_t = 174.3 \pm 5.1$ GeV. Also, the recent value of m_s seems to shift toward a slightly small one. Therefore, the revise values for those given in (2.1) are as follows: