Extension of the Standard Model by a gauged lepton flavor symmetry and leptogenesis

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Abstract

We study the minimal extensions of the Standard Model with three right-handed neutrinos by gauged U(1) lepton flavor symmetries. In some of those models, the mass matrix for the light neutrinos has the so-called two-zero-minor structure, namely, the inverse of the neutrino mass matrix has two vanishing components. Analyzing these conditions, we obtain all the CP phases, such as the Dirac CP phase δ and the Majorana CP phases α_2 and α_3, and the mass eigenvalues of the light neutrinos m_i as functions of the neutrino mixing angles θ_{12}, θ_{23}, and θ_{13}, and the squared mass differences Δm_{21}^2 and Δm_{31}^2. Furthermore, using these results, we also obtain the predictions for the sum of the neutrino masses $\Sigma_i m_i$ and the effective neutrino mass $\langle m_{\beta\beta}\rangle$. In addition, we also discuss the implication of our results for leptogenesis. Because space is limited, in this report, we show a part of our work.

1 Introduction

A gauged U(1) lepton flavor symmetry is one of the possibilities of extension of the Standard Model (SM) and it is known that $\mathrm{U}(1)_{L_i-L_j}$ gauge symmetries, where L_i represents the lepton number of generation associated with i $(= e, \mu, \tau)$, can be introduced without anomalies. We focus on the cases where the neutrino mass matrix has the so-called two-zero-minor structure, namely, the inverse of them has two vainishing components. In Ref. [1], the relation between gauged U(1) lepton flavor symmetries and structures of the neutrino mass matrix was comprehensively discussed. In the case of the minimal extended model by a $\mathrm{U}(1)_{L_\mu-L_\tau}$ gauge symmetry, we discussed the relation between two-zero-minor conditions and the neutrino parameters, such as the CP phases, the neutrino masses, and the effective neutrino mass, and gave the predictions for them in Ref. [2].

In the workshop, we presented results of the study [3], where we extended extra U(1) gauge symmetries to ones obtained as a linear combination of the $\mathrm{U}_{L_e-L_\mu}$, $\mathrm{U}(1)_{L_\mu-L_\tau}$, and $\mathrm{U}(1)_{B-L}$ gauge symmetries. Then, we discussed that relation as we have done in Ref. [2] and, in the case of the five U(1) gauge symmetries that were consistent with the resent neutrino oscillation data, we obtained all the CP phases, such as the Dirac CP phase δ and the Majorana CP phases α_2 and α_3, and the mass eigenstates of the light neutrinos as functions of the neutrino mixing angles θ_{12}, θ_{23}, and θ_{13}, and the squared mass differences Δm_{21}^2 and Δm_{31}^2. We also discussed the implication of our results for leptogenesis. However, since space is limited, we show only the derivation of the two-zero-minor conditions and the prediction for the sum of the neutrino masses in this report.[2]

2 Analyses of neutrino mass structure

Because of the anomaly-free condition, allowed linear combination of gauged U(1) lepton flavor symmetries are $\mathrm{U}(1)_{aL_e+bL_\mu-(a+b)L_\tau}$ and $\mathrm{U}(1)_{B+aL_e+bL_\mu+(3-a-b)L_\tau}$, where a and b are real

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[2] The details are written in Ref. [3].

numbers. To avoid verbose description, however, we consider only the $\mathrm{U}(1)_{L_\mu - L_\tau}$ case and analyze the neutrino mass matrix following Ref [2]. In the case of other U(1) symmetries, we can use the same method. In the minimal gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ model, the interaction terms relevant to neutrino masses are given by

$$
\begin{aligned}
\Delta\mathcal{L} = &-\lambda_e N_e^c (L_e \cdot H) - \lambda_\mu N_\mu^c (L_\mu \cdot H) - \lambda_\tau N_\tau^c (L_\tau \cdot H) \\
&- \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c - \lambda_{e\mu} \sigma N_e^c N_\mu^c - \lambda_{e\tau} \sigma^* N_e^c N_\tau^c + \text{h.c.} ,
\end{aligned} \tag{1}
$$

where the dots indicate the contraction of the $\mathrm{SU}(2)_L$ indices. After the Higgs field H and the singlet scalar σ acquire VEVs $\langle H \rangle = v/\sqrt{2}$ and $\langle \sigma \rangle$,[3] the Dirac and Majorana mass matrices are obtained as follows:

$$
\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix} , \qquad \mathcal{M}_R = \begin{pmatrix} M_{ee} & \lambda_{e\mu}\langle\sigma\rangle & \lambda_{e\tau}\langle\sigma\rangle \\ \lambda_{e\mu}\langle\sigma\rangle & 0 & M_{\mu\tau} \\ \lambda_{e\tau}\langle\sigma\rangle & M_{\mu\tau} & 0 \end{pmatrix} . \tag{2}
$$

The mass matrix for the light neutrinos is given by [4]

$$
\mathcal{M}_{\nu_L} \simeq -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T . \tag{3}
$$

We can obtain the mass eigenvalues of the light neutrinos by diagonalizing this matrix using a unitary matrix U (PMNS matrix [4] [5]):

$$
U^T \mathcal{M}_{\nu_L} U = \mathrm{diag}(m_1, m_2, m_3) . \tag{4}
$$

In this report, we consider only the $m_i \neq 0$ cases. For if $m_i = 0$ ($i = 1$ or 3), the mass matrix for the light neutrinos $\mathcal{M}_{\nu_L}$ is block-diagonal, and we cannot have desired mixing angles. From Eqs. (3) and (4),

$$
\mathcal{M}_{\nu_L}^{-1} = U \mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1}) U^T \simeq -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1} . \tag{5}
$$

In this model, $\mathcal{M}_D$ is diagonal and (μ,μ) and (τ,τ) components in $\mathcal{M}_R$ vanish, so these components in the inverse of $\mathcal{M}_{\nu_L}$ also have to vanish. These two conditions, which these components in $\mathcal{M}_{\nu_L}^{-1}$ have to satisfy, are given by

$$
\frac{1}{m_1} V_{\mu 1}^2 + \frac{1}{m_2} V_{\mu 2}^2 \, e^{i\alpha_2} + \frac{1}{m_3} V_{\mu 3}^2 \, e^{i\alpha_3} = 0 , \tag{6}
$$

$$
\frac{1}{m_1} V_{\tau 1}^2 + \frac{1}{m_2} V_{\tau 2}^2 \, e^{i\alpha_2} + \frac{1}{m_3} V_{\tau 3}^2 \, e^{i\alpha_3} = 0 , \tag{7}
$$

where the matrix V is defined by $U = V \cdot \mathrm{diag}(1, e^{i\alpha_2/2}, e^{i\alpha_3/2})$. We notice that neither the $\mathrm{U}(1)_{L_\mu - L_\tau}$-breaking singlet VEV $\langle\sigma\rangle$ nor Majorana masses M_{ee} and $M_{\mu\tau}$ appear in these conditions explicitly, and so the following discussions and results based on the above conditions are independent of these scales. Eqs. (6) and (7) are two complex equations, therefore, by solving these equations, we can obtain the Dirac CP phase δ, the Majorana CP phases $\alpha_{2,3}$, and the mass eigenvalue of the lightest neutrino m_1, as functions of the mixing angles θ_{12}, θ_{23}, and θ_{13}, and the squared mass differences Δm_{21}^2 and Δm_{32}^2. [5]

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[3]We can always take the VEV of σ to be real by using $\mathrm{U}(1)_{L_\mu - L_\tau}$ transformations.

[4]We follow the convention of the Particle Data Group [6].

[5]For concrete calculations and explicit expressions, see Ref [2].

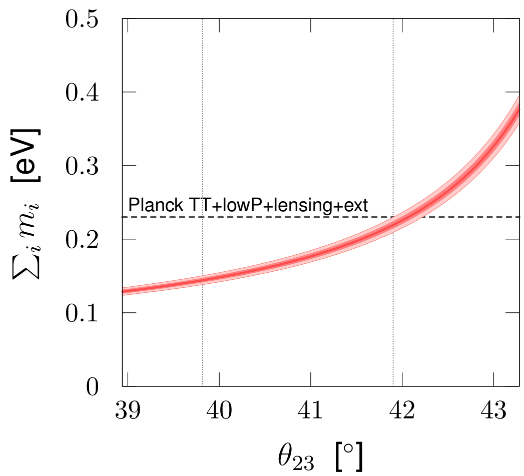

Figure 1: The prediction for the sum of the neutrino masses as a function of θ_{23}. The dark (light) red band shows the uncertainty coming from the 1σ (2σ) errors in the parameters θ_{12}, θ_{13}, δm^2, and Δm^2. The entire region is within the 2σ range of θ_{23}, while its 1σ range is between the thin vertical dotted lines. We also show in the black dashed line the present limit imposed by the Planck experiment: $\sum_i m_i < 0.23$ eV (Planck TT+lowP+lensing+ext) [7].

Since space is limited, we show only the prediction for the sum of the neutrino masses as a function of θ_{23} in Fig. 1, where the dark (light) red band shows the uncertainty coming from the 1σ (2σ) errors in the parameters other than θ_{23}. We also show in the black dashed line the present limit imposed by the Planck experiment: $\Sigma_i m_i < 0.23$ eV (Planck TT+lowP+lensing+ext) [7]. From this figure, we find that a wide range of the parameter region predicts a value of $\Sigma_i m_i$ which is below the present limit, though a part of the parameter region has already been disfavored by the Planck limit.

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