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Fermion mass hierarchy and mixing using generalized CP transformations

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In this work, we have obtained maximal values for atmospheric mixing angle and CP violating Dirac phase of the lepton sector in a type II seesaw scenario, by modifying a model originally proposed by Grimus and Lavoura, where we have used CP and other discrete symmetries. In order to make predictions about neutrino mass ordering and the smallness of the reactor angle, we have obtained some conditions on the elements of the neutrino mass matrix of our model. Within the same framework, we have studied quark masses and mixing by using a certain texture in a higher-dimensional model.

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1. Introduction

From the global fits to neutrino oscillation data it is known that the three mixing angles in lepton sector are close to the tribimaximal (TBM) mixing pattern [1–3], where the mixing angles have the following values: $\sin^2\theta_{23} = \frac{1}{2}$, $\sin^2\theta_{12} = \frac{1}{3}$ and $\sin^2\theta_{13} = 0$. Apart from these mixing angles, the CP violating Dirac phase $\delta_{\rm CP}$ in lepton sector is yet to be measured precisely. However, from the global fits to neutrino oscillation data [4], the best fit value for $\delta_{\rm CP}$ is around $\pi(\frac{3\pi}{2})$ in the case of normal(inverted) ordering of neutrino masses. The TBM value for θ_{23} and $\delta_{\rm CP} = \frac{3\pi}{2}$ are still allowed in the 3σ ranges for these observables in both the cases of normal and inverted ordering of neutrino masses. The above mentioned values for θ_{23} and $\delta_{\rm CP}$ are considered to be maximal. To explain the maximal values for θ_{23} and $\delta_{\rm CP}$, Harrison and Scott have proposed $\mu-\tau$ symmetry in combination with CP symmetry [5], which together is called $\mu-\tau$ reflection symmetry.

In this work we have obtained $\mu-\tau$ reflection mass matrix pattern in type II seesaw framework by introducing three Higgs doublets and one scalar triplet, along with the imposition of generalized CP symmetry. Three Higgs doublets will give masses to charged leptons, while Higgs triplet will be used for neutrino mass generation. In the same model we have explained quark mass hierarchy and mixing by following some particular texture.

2. Lepton mixing

In this work we have modified a scenario, originally proposed by Grimus and Lavoura [6], to predict the maximal atmospheric angle and maximal CP violation. We propose scalar Higgs doublets $\phi_i = (\phi_i^+, \phi_i^0)^T$, where $i = 1,2,3$, in order to give masses to charged leptons, and also a scalar Higgs triplet Δ to give masses to neutrinos. We denote the lepton doublets and singlets by $D_{\alpha L} = (\nu_{\alpha L}, \alpha_L)^T$ and α_R, where $\alpha = e, \mu, \tau$, respectively. The CP transformations on the lepton fields are defined as

$$L_{\alpha L} \to iS_{\alpha\beta}\gamma^0 C\bar{L}^T_{\beta L}, \quad \alpha_R \to iS_{\alpha\beta}\gamma^0 C\bar{\beta}^T_R, \quad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \tag{1}$$

where $\alpha, \beta = e, \mu, \tau$. C is the charge conjugation matrix and γ^0 is one of the Dirac matrices. Under CP symmetry, scalar fields transform as $\phi_{1,2}, \Delta \to \phi^*_{1,2}, \Delta^*, \quad \phi_3, \to -\phi^*_3$. In addition to the invariance under the above mentioned CP transformations, one needs to impose conservation of $U(1)_{L_\alpha}$ and Z_2 symmetries. Here, $U(1)_{L_\alpha}$ is the lepton number symmetry for the individual family of leptons. Under Z_2 symmetry, only the e_R and ϕ_1 change sign. With the above mentioned charge assignments, the charged lepton masses can be generated [7]. However, muon and tau masses can be of the same order. Hence, to explain the hierarchy in masses of muon and tau, K symmetry is introduced under which $\mu_R \to -\mu_R$ and $\phi_2 \leftrightarrow \phi_3$. After imposing the K symmetry into our model, we get

$$\frac{m_\mu}{m_\tau} = \left|\frac{v_2 - v_3}{v_2 + v_3}\right|. \tag{2}$$

Since the scalar potential of this model should also respect the K symmetry, we should get $v_2 = v_3$, and hence, $m_\mu = 0$. Now, to explain a non-zero but small m_μ, soft breaking of K symmetry can be introduced into the scalar potential of this model [8] which we describe later on.

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Now, the Yukawa couplings for neutrinos can be written as

$$\mathcal{L}_Y = \frac{1}{2} \sum_{\alpha,\beta=e,\mu,\tau} Y^{\nu}_{\alpha\beta} \bar{D}^{c}_{\alpha L} i\sigma_2 \Delta D_{\beta L} + h.c.. \tag{3}$$

Here, $D^c_{\alpha L}$ is the charge conjugated doublet for $D_{\alpha L}$ and σ_2 is a Pauli matrix. The terms in the above Lagrangian break the lepton number symmetry U_{L_α} explicitly. We consider this technically natural, since in the limit that the symmetry U_{L_α} is exact, the neutrino masses become zero in this model. Hence to explain the smallness of neutrino masses we break U_{L_α} symmetry by a small amount. As a result of this, we take $Y^{\nu}_{\alpha\beta}$ to be small, which are $\sim 10^{-3}$. Due to the invariance under CP symmetry, neutrino Yukawa couplings satisfy $SY^{\nu}S = (Y^{\nu})^*$. Now, from Eq. (3), we get the mass matrix for neutrinos, which is given by $M_\nu = Y^\nu v_\Delta$. If v_Δ is real, we get M_ν to be in $\mu - \tau$ reflection symmetric form, and by using the results of [6], our model predicts maximal atmospheric angle and also maximal CP violation.

We have written the full scalar potential which involves three scalar doublets and one scalar triplet, in order to show that triplet scalar can acquire real VEV and also to explain the hierarchy in muon and tau masses [7]. To achieve this, in addition to previously mentioned symmetries, we have added one Z_3 symmetry, under which we have $\mu_R, \tau_R \to \Omega\mu_R, \tau_R$ and $\phi_{2,3} \to \Omega^2\phi_{2,3}$, where Ω is the cube root of unity. Z_3 symmetry is introduced to give real VEV of triplet scalar. Now, we parametrize the VEVs of scalar fields as follows

$$\langle\phi_1^0\rangle = v_1, \quad \langle\phi_2^0\rangle = v_2 = v\cos\sigma e^{i\alpha}, \quad \langle\phi_3^0\rangle = v_3 = v\sin\sigma e^{i\beta}, \quad \langle\Delta^0\rangle = v_\Delta = v' e^{i\theta}. \tag{4}$$

Here, v_1, v, v' are real. Then, plugging the above parametrization in scalar potential, we have found a minimum at $\sigma = \frac{\pi}{4}$, $\zeta = (\alpha - \beta) = 0$ and $\theta = 0$. Since $\zeta = 0$ corresponds to $m_\mu = 0$, we introduce $K-$violating terms into the model. As a result of this, the above mentioned minimum can be shifted by small deviations in δ_0, δ_ζ as

$$\sigma = \frac{\pi}{4} - \frac{\delta_0}{2}, \quad \zeta = 0 + \delta_\zeta. \tag{5}$$

Now, after finding the minimum, we can see that $\delta_0, \delta_\zeta \neq 0$. After that, we get

$$\frac{m_\mu}{m_\tau} = \frac{1}{2}|\delta_0 + i\delta_\zeta|. \tag{6}$$

Using the above equation, the required hierarchy between muon and tau leptons can be explained if we take $\delta_0, \delta_\zeta \sim 0.1$. In our model we have obtained some conditions on neutrino Yukawa couplings, which can predict neutrino mass ordering and also the smallness of the reactor angle [7].

3. Quark masses and mixing

In this model, we have also explained quark masses and mixing. We denote three families of quark doublets, up- and down-type singlets as Q_{jL}, u_{jR} and d_{jR}, respectively. We propose a scalar field X which is singlet under standard model gauge group. We assume all the quark doublets to be singlets under the symmetry $K \times Z_2 \times Z_3$. On the other hand, all the right-handed quark fields are singlets under $K \times Z_3$ and they are odd under Z_2 symmetry. X field is singlet under $K \times Z_3$ but is odd under Z_2. Both the quark and X fields transform under CP symmetry as

$$Q_{jL} \to i\gamma^0 C \bar{Q}_{jL}^T, \quad u_{jR} \to i\gamma^0 C \bar{u}_{jR}^T, \quad d_{jR} \to i\gamma^0 C \bar{d}_{jR}^T, \quad X \to X^*. \tag{7}$$

Now, with these charge assignments and with higher dimensional Yukawa couplings of quarks, the mass matrices for up and down type quarks take the following form

$$M_u = \begin{pmatrix} h_{11}^u \epsilon^6 & h_{12}^u \epsilon^4 & h_{13}^u \epsilon^4 \\ h_{21}^u \epsilon^4 & h_{22}^u \epsilon^2 & h_{23}^u \epsilon^2 \\ h_{31}^u \epsilon^4 & h_{32}^u \epsilon^2 & h_{33}^u \end{pmatrix} v_1, \quad M_d = \begin{pmatrix} h_{11}^d \epsilon^6 & h_{12}^d \epsilon^6 & h_{13}^d \epsilon^6 \\ h_{21}^d \epsilon^{10} & h_{22}^d \epsilon^4 & h_{23}^d \epsilon^4 \\ h_{31}^d \epsilon^{10} & h_{32}^d \epsilon^4 & h_{33}^d \epsilon^2 \end{pmatrix} v_1. \tag{8}$$

Here, $\epsilon = \frac{\langle X \rangle}{M}$. The form of $M_{u,d}$ is similar to the corresponding matrices of Refs. [9, 10]. Hence, after diagonalizing the above matrices, the masses and mixing angles for quarks, up to leading order in $|\epsilon|$, are given by

$$\begin{aligned}
&(m_t, m_c, m_u) \approx (|h_{33}^u|, |h_{22}^u||\epsilon|^2, |h_{11}^u - h_{12}^u h_{21}^u / h_{22}^u||\epsilon|^6) v_1, \\
&(m_b, m_s, m_d) \approx (|h_{33}^d||\epsilon|^2, |h_{22}^d||\epsilon|^4, |h_{11}^d||\epsilon|^6) v_1, \\
&|V_{us}| \approx \left| \frac{h_{12}^d}{h_{22}^d} - \frac{h_{12}^u}{h_{22}^u} \right| |\epsilon|^2, \quad |V_{cb}| \approx \left| \frac{h_{23}^d}{h_{33}^d} - \frac{h_{23}^u}{h_{33}^u} \right| |\epsilon|^2, \quad |V_{ub}| \approx \left| \frac{h_{13}^d}{h_{33}^d} - \frac{h_{12}^u h_{23}^d}{h_{22}^u h_{33}^d} - \frac{h_{13}^u}{h_{33}^u} \right| |\epsilon|^4 \\
&\arg(V_{ub}) \approx 4\arg(\epsilon).
\end{aligned} \tag{9}$$

Now, the above expressions can be fitted to the experimental quark masses and mixing, and we have found the following values.

$$\begin{aligned}
&(|h_{33}^u|, |h_{22}^u|, |h_{11}^u - h_{12}^u h_{21}^u / h_{22}^u|) \approx (1.4, 0.31, 0.49), \\
&(|h_{33}^d|, |h_{22}^d|, |h_{11}^d|) \approx (1.03, 0.69, 1.05), \\
&(h_{12}^d, h_{12}^u, h_{23}^d, h_{23}^u, h_{13}^d, h_{13}^u) \approx (1.49, -1.45, 0.69, -0.8, 1.12, 1.0), \\
&\arg(\epsilon) \approx -0.3
\end{aligned} \tag{10}$$

From the numerical values given above, we can see that the magnitudes of all Yukawa couplings are less than about 1.5. As all the quark Yukawa couplings are generated by higher dimensional operators, we have studied the UV completion by introducing flavons and vector like quarks [7].

4. Conclusions

In this work we have proposed a model which explains the maximal θ_{23} and maximal $\delta_{\rm CP}$ in the lepton sector via a type II seesaw mechanism and $\mu - \tau$ reflection symmetry, where we have introduced three Higgs doublets and one scalar Higgs triplet. $\mu - \tau$ symmetric mass matrix is generated under a condition that the VEV of triplet field should be real. We have achieved this condition by introducing the discrete symmetry Z_3. Moreover, due to $\mu - \tau$ reflection symmetry of our model, the masses for muon and tau can be of the same order. We have explained the hierarchy in these masses by introducing K symmetry and violating it explicitly by a small amount. We have demonstrated the above mentioned facts by studying the minimization of the scalar potential of our model. After employing a certain texture for quark Yukawa couplings, we have consistently explained the quark masses and mixing pattern in our model.

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