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# Deviation from tri-bimaximal mixing and large reactor mixing angle

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**Abstract**

Recent observations for a non-zero $\theta_{13}$ have come from various experiments. We study a model of lepton mixing with a 2–3 flavor symmetry to accommodate the sizable $\theta_{13}$ measurement. In this work, we derive deviations from the tri-bimaximal (TBM) pattern arising from breaking the flavor symmetry in the neutrino sector, while the charged leptons contribution has been discussed in a previous work. Contributions from both sectors towards accommodating the non-zero $\theta_{13}$ measurement are presented.


## 1. Introduction

Neutrino oscillations can be parametrized in terms of three mixing angles $\theta_{12}$, $\theta_{13}$, $\theta_{23}$ and Dirac ($\delta$) and Majorana ($\zeta_1$, $\zeta_2$) CP violating phases

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} P_\nu, \tag{1}$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, and $P_\nu \equiv \{1, e^{i\zeta_1}, e^{i\zeta_2}\}$ is a diagonal phase matrix, which is physically relevant if neutrinos are Majorana particles. The experiments have shown that the angles of lepton mixing are relatively larger than their counterparts in the quark sector. Recent

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data from the Double Chooz [1], Daya Bay [2], RENO [3] experiments as well as latest T2K [4] and MINOS [5] experiments have yielded non-zero values for $\theta_{13}$. The best-fit values for the mixing angles are given as [6]

$$\begin{aligned}
&\sin^2\theta_{12} = 0.320, \\
&\sin^2\theta_{23} = 0.427\ (0.600) \quad \text{(for normal (inverted) hierarchy)}, \\
&\sin^2\theta_{13} = 0.0246\ (0.0250) \quad \text{(for normal (inverted) hierarchy)}. \qquad (2)
\end{aligned}$$

The distribution of the flavors in the mass eigenstates, corresponding to the best-fit values of the mixing angles, has shown that the leading order mixing method is a quite successful way to describe the lepton mixing. The most common patterns that have been discussed in the literatures to describe the lepton mixing, which may arise from discrete symmetries, are called; democratic (DC) [7], bimaximal (BM) [8], and tri-bimaximal (TBM) [9] mixing matrix. Recently, a pattern has been proposed to link the lepton and quark sectors so-called Tri-bimaximal-Cabibbo mixing [10]. Many previous studies have considered the TBM form in the symmetric limit of different flavor symmetries [11–20]. Contributions from the charged lepton sector to the leptonic mixing have been studied previously [21,22]. The recent $\theta_{13}$ measurement has been discussed [23–27], several papers have considered deviations from the charged lepton sector [28,29]. Early studies of a sizable $\theta_{13}$ have been conducted previously [30].

The leptonic mixing matrix is obtained from the contributions of the diagonalization of the charged lepton and neutrino mass matrices. Many models have been introduced to study the leptonic mixing in the basis where the charged lepton mass matrix is diagonal. Our approach considers both contributions from the charged lepton and neutrino sector to obtain the leading order leptonic mixing as well as deviations from it. One of the central ideas of this approach is the requirement that the mass matrices, in a symmetric limit, be diagonalized by unitary matrices composed of pure numbers independent of the parameters of the mass matrices. If one starts with a 2–3 symmetric mass matrix for the charged lepton sector and requires it to be diagonalized by unitary matrices of pure numbers one recovers the decoupled 2–3 symmetry; decoupling of the first generation from the second and third generations. This helps in understanding the mass splitting between the first generation from the second and third generations.

Before we begin our analysis we would like to remark the fact that the quark and charged leptons exhibit similar hierarchical structures. We therefore assume the same flavor structure for them. One can use similar parametrization and flavor symmetric limit in the quark and charged lepton sector. The discussion of the 2–3 flavor symmetry in the quark sector can be found in Ref. [31].

In Ref. [32], they have considered the decoupled 2–3 symmetry as the flavor symmetry in the charged lepton sector. The contributions of the charged lepton and neutrino sector have been discussed in Ref. [32] with the Bimaximal (BM) pattern being the leading order term of the lepton mixing. In this work, we assume a certain texture for the neutrino mass matrix with the third generation decoupled from the first two generations. Requiring the elements of the unitary matrix that diagonalizes the neutrino mass matrix to be independent of the mass parameters, the leptonic mixing turns out to have the TBM form in the symmetric limit under a certain condition.

In our model, we introduce a Lagrangian that extends the SM particle content by three right-handed neutrinos, three complex singlet scalar fields, and an additional Higgs doublet.[1]

[1] Some recent motivations for considering two Higgs doublet models can be found in Ref. [33].