Research Article

Investigating the Hybrid Textures of Neutrino Mass Matrix for Near Maximal Atmospheric Neutrino Mixing

Madan Singh

Department of Physics, National Institute of Technology, Kurukshetra, Haryana 136119, India

Correspondence should be addressed to Madan Singh; singhmadan179@gmail.com

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We have studied that the implication of a large value of the effective Majorana neutrino mass in case of neutrino mass matrices has either two equal elements and one zero element (popularly known as hybrid texture) or two equal cofactors and one zero minor (popularly known as inverse hybrid texture) in the flavor basis. In each of these cases, four out of sixty phenomenologically possible patterns predict near maximal atmospheric neutrino mixing angle in the limit of large effective Majorana neutrino mass. This feature remains irrespective of the experimental data on solar and reactor mixing angles. In addition, we have also performed the comparative study of all the viable cases of hybrid and inverse hybrid textures at 3σ CL.

1. Introduction

In leptonic sector, the reactor mixing angle (θ_{13}) has been established to a reasonably good degree of precision [1–6], and its nonzero and relatively large value has not only provided an opportunity in exploring CP violation and the neutrino mass ordering in the future experiments but has also highlighted the puzzle of neutrino mass and mixing pattern. In spite of the significant developments made over the years, there are still several intriguing questions in the neutrino sector which remain unsettled. For instance, the present available data is unable to throw any light on the neutrino mass spectrum, which may be normal/inverted and may even be degenerate. Another important issue is the determination of octant of atmospheric mixing angle θ_{23} , which may be greater than or less than or equal to 45° . The determination of the nature of neutrinos whether Dirac or Majorana also remains an open question. The observation of neutrinoless double beta ($0\nu\beta\beta$) decay would eventually establish the Majorana nature of neutrinos.

The effective Majorana mass term related to $0\nu\beta\beta$ decay can be expressed as

$$|M|_{ee} = \left| m_1 c_{12}^2 c_{13}^2 e^{2i\rho} + m_2 s_{12}^2 c_{13}^2 e^{2i\sigma} + m_3 s_{13}^2 \right|. \quad (1)$$

Data from KamLAND-Zen experiment has presented an improved search for neutrinoless double-beta ($0\nu\beta\beta$) decay [7] and it is found that $|M|_{ee} < (0.061-0.165)$ eV at 90% (or $<2\sigma$) CL. For recent reviews on $0\nu\beta\beta$ decay see [8–13].

In the lack of any convincing theory, several phenomenological ideas have been proposed in the literature so as to restrict the form of neutrino mass matrix, such as some elements of neutrino mass matrix that are considered to be zero or equal [14–21] or some cofactors of neutrino mass matrix to be either zero or equal [19, 22–27]. Specifically, mass matrices with zero textures (or cofactors) have been extensively studied [14–18, 22–24] due to their connections to flavor symmetries. In addition, texture structures with one zero element (or minor) and an equality between two independent elements (or cofactors) in neutrino mass matrix have also been studied in the literature [20, 21, 26, 27]. Such form of texture structures sets to one constraint equation and thus reduces the number of real free parameters of neutrino mass matrix to seven. Hence they are considered as predictive as the well-known two-zero textures and can also be realised within the framework of seesaw mechanism. Out of sixty possibilities, only fifty-four are found to be compatible with the neutrino oscillation data [21] for texture structures having one zero element and equal matrix elements in the

neutrino mass matrix (1TEE), while for texture with one vanishing minor and equal cofactors in the neutrino mass matrix (1TEC) only fifty-two cases are able to survive the data [26, 27].

The purpose of present paper is to investigate the implication of large effective neutrino mass $|M|_{ee}$ on 1TEE and 1TEC structures of neutrino mass matrix, while taking into account the assumptions of [28, 29]. The consideration of large $|M|_{ee}$ is motivated by the extensive search for this parameter in the ongoing $0\nu\beta\beta$ experiments. The implication of large $|M|_{ee}$ has earlier been studied for the viable cases of texture two-zero and two-vanishing minor, respectively [28, 29]. Grimus et al. [30] also predicted the near maximal atmospheric mixing for two-zero textures when supplemented with the assumption of quasi-degenerate mass spectrum. However, the observation made in all these analyses is independent of solar and reactor mixing angles. Motivated by these works, we find that only four out of sixty cases are able to predict near maximal θ_{23} for 1TEE and 1TEC, respectively. In addition, the analysis also hints towards the indistinguishable feature of 1TEE and 1TEC. To present the indistinguishable nature of the 1TEE and 1TEC texture structures, we have then carried out a comparative study of all the viable cases of 1TEE and 1TEC at 3σ CL. The similarity between texture zero structures with one mass ordering and corresponding cofactor zero structures with the opposite mass ordering has earlier been noted in [31–33]. In [19], the strong similarities have also been noted between the texture structures with two equalities of elements and structures with two equalities of cofactors in neutrino mass matrix, with opposite mass ordering.

The rest of the paper is planned in the following manner. In Section 2, we shall discuss the methodology to obtain the constraint equations. Section 3 is devoted to numerical analysis. In the end we will summarize our result.

2. Methodology

The effective Majorana neutrino mass matrix (M_ν) contains nine parameters which include three neutrino masses (m_1, m_2, m_3), three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), and three CP violating phases (δ, ρ, σ). In the flavor basis, the Majorana neutrino mass matrix can be expressed as follows:

$$\begin{aligned} \frac{\lambda_1}{\lambda_3} &= \frac{P(U_{a3}U_{b3}U_{\alpha2}U_{\beta2} - U_{a2}U_{b2}U_{\alpha3}U_{\beta3}) + (U_{a2}U_{b2}U_{c3}U_{d3} - U_{a3}U_{b3}U_{c2}U_{d2})}{P(U_{a2}U_{b2}U_{\alpha1}U_{\beta1} - U_{a1}U_{b1}U_{\alpha2}U_{\beta2}) + (U_{a1}U_{b1}U_{c2}U_{d2} - U_{a2}U_{b2}U_{c1}U_{d1})}, \\ \frac{\lambda_2}{\lambda_3} &= \frac{P(U_{a1}U_{b1}U_{\alpha3}U_{\beta3} - U_{a3}U_{b3}U_{\alpha1}U_{\beta1}) + (U_{a3}U_{b3}U_{c1}U_{d1} - U_{a1}U_{b1}U_{c3}U_{d3})}{P(U_{a2}U_{b2}U_{\alpha1}U_{\beta1} - U_{a1}U_{b1}U_{\alpha2}U_{\beta2}) + (U_{a1}U_{b1}U_{c2}U_{d2} - U_{a2}U_{b2}U_{c1}U_{d1})}, \end{aligned} \quad (6)$$

where $P = e^{i(\phi_\alpha + \phi_\beta - \phi_c - \phi_d)}$ is a phase factor. Similarly, in case of inverse hybrid texture structure (1TEC) of M_ν , we can express the ratios of mass eigenvalues as [26, 27] follows:

$$\frac{\lambda_1}{\lambda_3} = \frac{A_1 B_2 - A_2 B_1}{A_2 B_3 - A_3 B_2},$$

$$M_\nu = P_l U P_\nu M^{\text{diag}} P_\nu^T U^T P_l^T, \quad (2)$$

where $M^{\text{diag}} = \text{diag}(m_1, m_2, m_3)$ is the diagonal matrix of neutrino masses and U is the flavor mixing matrix, and

$$\begin{aligned} P_\nu &= \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \\ P_l &= \begin{pmatrix} e^{i\phi_e} & 0 & 0 \\ 0 & e^{i\phi_\mu} & 0 \\ 0 & 0 & e^{i\phi_\tau} \end{pmatrix}, \end{aligned} \quad (3)$$

where P_ν is diagonal phase matrix containing Majorana neutrinos ρ, σ . P_l is unobservable phase matrix and depends on phase convention. Equation (2) can be rewritten as

$$M_\nu = P_l U \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} U^T P_l^T, \quad (4)$$

where $\lambda_1 = m_1 e^{2i\rho}$, $\lambda_2 = m_2 e^{2i\sigma}$, $\lambda_3 = m_3$. For the present analysis, we consider the following parameterization of U [20]:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -c_{12}s_{23}s_{13} - s_{12}c_{23}e^{-i\delta} & -s_{12}s_{23}s_{13} + c_{12}c_{23}e^{-i\delta} & s_{23}c_{13} \\ -c_{12}c_{23}s_{13} + s_{12}s_{23}e^{-i\delta} & -s_{12}c_{23}s_{13} - c_{12}s_{23}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (5)$$

where $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$. Here, U is a 3×3 unitary matrix consisting of three flavor mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one Dirac CP-violating phase δ .

For hybrid texture structure (1TEE) of M_ν , we can express the ratios of neutrino mass eigenvalues in terms of the mixing matrix elements as [21]

$$\frac{\lambda_2}{\lambda_3} = \frac{A_1 B_2 - A_2 B_1}{A_3 B_1 - A_1 B_3}, \quad (7)$$

where

$$A_i = (U_{pj}U_{qj}U_{rk}U_{sk} - U_{tj}U_{uj}U_{vk}U_{wk}) + (j \longleftrightarrow k),$$

FIGURE 1: Correlation plots for textures B_2 ((a) NO and (b) IO) and C_7 for ((c) NO and (d) IO) at 3σ CL for 1TEE. The symbols have their usual meaning. The horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e., $|M|_{ee} < 0.165$ eV) at 90% CL, given in KamLAND-Zen experiment [7].

$$\begin{aligned}
 B_i = & (-1)^{m+n} Q (U_{aj} U_{bj} U_{ck} U_{dk} - U_{ej} U_{fj} U_{gk} U_{hk}) \\
 & - (-1)^{m'+n'} (U_{a'j} U_{b'j} U_{c'k} U_{d'k} - U_{e'j} U_{f'j} U_{g'k} U_{h'k}) \\
 & + (j \longleftrightarrow k),
 \end{aligned} \tag{8}$$

with (i, j, k) a cyclic permutation of $(1, 2, 3)$ and $Q = e^{i(\phi_a + \phi_b + \phi_c + \phi_d - \phi_{a'} - \phi_{b'} - \phi_{c'} - \phi_{d'})}$ is phase factor.

Using the above expressions, we can obtain the magnitude of neutrino mass ratios, $\alpha \equiv |\lambda_1|/|\lambda_3|$ and $\beta \equiv |\lambda_2|/|\lambda_3|$ in each texture structure, and the Majorana phases (ρ, σ) can be given as $\rho = (1/2) \arg(\lambda_1/\lambda_3)$ and $\sigma = (1/2) \arg(\lambda_2/\lambda_3)$.

The solar and atmospheric mass squared differences ($\delta m^2, \Delta m^2$), where δm^2 corresponds to solar mass-squared difference and Δm^2 corresponds to atmospheric mass-squared difference, can be defined as [20]

$$\delta m^2 = (m_2^2 - m_1^2),$$

$$\Delta m^2 = m_3^2 - \frac{1}{2} (m_1^2 + m_2^2). \tag{9}$$

The experimentally determined solar and atmospheric neutrino mass-squared differences can be related to neutrino mass ratios (α, β) as

$$R_\nu \equiv \frac{\delta m^2}{|\Delta m^2|} = \frac{2(\beta^2 - \alpha^2)}{|2 - (\beta^2 + \alpha^2)|}, \tag{10}$$

and the three neutrino masses can be determined in terms of α, β as

$$\begin{aligned}
 m_3 &= \sqrt{\frac{\delta m^2}{\beta^2 - \alpha^2}}, \\
 m_2 &= m_3 \beta, \\
 m_1 &= m_3 \alpha.
 \end{aligned} \tag{11}$$

FIGURE 2: Correlation plots for textures B_2 ((a) NO and (b) IO) and C_7 for ((c) NO and (d) IO) at 3σ CL for 1TEE. The symbols have their usual meaning. The horizontal line indicates the upper limit on reactor mixing angle $\theta_{13} < 8.9^\circ$, as given in Table 1.

Among the sixty logically possible cases of 1TEE or ITEC texture structures, there are certain pair, which exhibit similar phenomenological implications and are related via permutation symmetry [21, 26, 27]. This corresponds to permutation of the 2-3 rows and 2-3 columns of M_ν . The corresponding permutation matrix can be given by

$$P_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}. \quad (12)$$

With the help of permutation symmetry, one obtains the following relations among the neutrino oscillation parameters:

$$\begin{aligned} \theta_{12}^X &= \theta_{12}^Y, \\ \theta_{23}^X &= 90^\circ - \theta_{23}^Y, \\ \theta_{13}^X &= \theta_{13}^Y, \\ \delta^X &= \delta^Y - 180^\circ, \end{aligned} \quad (13)$$

where X and Y denote the cases related to 2-3 permutation. The following pair among sixty cases are related via permutation symmetry:

$$\begin{aligned} &(A_1, A_1); (A_2, A_8); (A_3, A_7); (A_4, A_6); (A_5, A_5); \\ &(A_9, A_{10}); (B_1, C_1) \\ &(B_2, C_7); (B_3, C_6); (B_4, C_5); (B_5, C_4); \\ &(B_6, C_3); (B_7, C_2); (B_8, C_{10}) \\ &(B_9, C_9); (B_{10}, C_8); (D_1, F_2); (D_2, F_1); (D_3, F_4); \\ &(D_4, F_3) \\ &(D_5, F_5); (D_6, F_9); (D_7, F_8); (D_8, F_7); (D_9, F_6); \\ &(D_{10}, F_{10}) \\ &(E_1, E_2); (E_3, E_4); (E_5, E_5); (E_6, E_9); (E_7, E_8); \\ &(E_{10}, E_{10}). \end{aligned}$$

Clearly we are left with only thirty-two independent cases. It is worthwhile to mention that cases A_1 , A_5 , E_5 , and E_{10} are invariant under the permutations of 2 and 3 rows and columns.

FIGURE 3: Correlation plots for textures B_2 ((a) NO and (b) IO) and C_7 for ((c) NO and (d) IO) at 3σ CL for ITEC. The symbols have their usual meaning. The horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e., $|M|_{ee} < 0.165$ eV) at 90% ($<2\sigma$) CL, given in KamLAND-Zen experiment [7].

3. Numerical Analysis

The experimental constraints on neutrino parameters at 3σ confidence levels (CL) are given in Table 1. The classification of sixty phenomenologically possible cases of ITEE and ITEC is done in the nomenclature, given by Wang et al. in [26, 27]. All the sixty cases are divided into six categories A, B, C, D, and E (Table 2). In [26, 27], it is found that the phenomenological results of cases belonging to ITEC (or ITEE) are almost similar to each other due to permutation symmetry. For the purpose of calculation, we have used the latest experimental data on neutrino mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2$) and mass squared differences ($\Delta m^2, \delta$) at 3σ CL [5, 6].

3.1. Near Maximal Atmospheric Mixing for ITEE and ITEC Texture Structures. As a first step of the analysis, all the sixty cases of ITEE and ITEC have been investigated in the limit of large $|M|_{ee}$. For the analysis, we have incorporated the assumptions of [28, 29], wherein authors have considered the

lower bound on $|M|_{ee}$ to be large (i.e., $|M|_{ee} > 0.08$ eV). The upper bound on $|M|_{ee}$ is chosen to be more conservative; that is, $|M|_{ee} < 0.5$ eV at 3σ CL [10]. The input parameters ($\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2, \delta$) are generated by the method of random number generation. The three neutrino mixing angles and Dirac-type CP-violating phase δ are varied between 0° to 90° and 0° to 360° , respectively. However, the mass-squared differences ($\delta m^2, \Delta m^2$) are varied randomly within their 3σ experimental range [5, 6]. For the numerical analysis, we follow the same procedure as discussed in [20]. The main results and discussion are summarized as follows.

In Figures 1, 2, 3, 4, 5, and 6, it is explicitly shown that the octant of θ_{23} is well restricted for B_2, C_7, D_3, F_4 of ITEE and ITEC texture structures, respectively. However, for the remaining cases, the value of θ_{23} is unconstrained like other oscillation parameters. Apart from restricting the octant of θ_{23} , the analysis also ensures the quasi-degenerate mass ordering for these cases similar to the observation of [28–30]. From Figures 1(a), 1(b), 3(a), and 3(b), it is clear that,

FIGURE 4: Correlation plots for textures B_2 ((a) NO and (b) IO) and C_7 for ((c) NO and (d) IO) at 3σ CL for ITEC. The symbols have their usual meaning. The horizontal line indicates the upper limit on reactor mixing angle $\theta_{13} < 8.9^\circ$, as given in Table 1.

TABLE 1: Current neutrino oscillation parameters from global fits at 3σ confidence level [5, 6]. NO (IO) refers to normal (inverted) neutrino mass ordering.

Parameter	Best fit	3σ
δm^2 [10^{-5} eV 2]	7.50	7.03–8.09
$ \Delta m_{31}^2 $ [10^{-3} eV 2] (NO)	2.52	2.407–2.643
$ \Delta m_{31}^2 $ [10^{-3} eV 2] (IO)	2.52	2.39–2.63
θ_{12}	33.56°	31.3° – 35.99°
θ_{23} (NO)	41.6°	38.4° – 52.8°
θ_{23} (IO)	50.0°	38.8° – 53.1°
θ_{13} (NO)	8.46°	7.99° – 8.90°
θ_{13} (IO)	8.49°	8.03° – 8.93°
δ (NO)	261°	0° – 360°
δ (IO)	277°	145° – 391°

for increasing value of $|M|_{ee}$, atmospheric mixing angle θ_{23} approaches to maximal value for the structure B_2 of ITEE and ITEC for both normal ordering (NO) and inverted ordering (IO). In Figures 2 and 4, it is explicitly shown that for cases B_2 and C_7 the quadrant of θ_{23} is already decided without the

experimental input of the mixing angles. For ITEE, we have $\theta_{23} < 45^\circ$ for NO and $\theta_{23} > 45^\circ$ for IO, whereas for ITEC, $\theta_{23} > 45^\circ$ for NO, while $\theta_{23} < 45^\circ$ for IO (Figures 2(a), 2(b), 4(a), and 4(b)). Clearly the correlation plots of case B_2 are indistinguishable for ITEE and ITEC, if neutrino mass

FIGURE 5: Correlation plots for textures D_3 ((a), (c)) and F_4 ((b), (d)) with IO for 1TEE at 3σ CL. The symbols have their usual meaning. In (a) and (b), colored horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e., $|M|_{ee} < 0.165$ eV) at 90 ($<2\sigma$)% CL, given in KamLAND-Zen experiment [7]. In (c) and (d), we have shown the upper limit on reactor mixing angle θ_{13} .

ordering is not considered as also pointed out earlier. Similar conclusion can be drawn for structure C_7 since both are related through 2-3 exchange symmetry (Figures 2(c), 2(d), 4(c), and 4(d)). Apart from the prediction of near maximality of θ_{23} , cases B_2 and C_7 also predict $\delta \simeq 90^\circ, 270^\circ$ for 1TEE and 1TEC, respectively, if experimental range of mixing angles is considered as in Table 2. Figures 2(a) and 2(c) for NO and Figures 2(b) and 2(d) for IO depict the 2-3 interchange symmetry between cases B_2 and C_7 for 1TEE. Similar phenomenological observation is shown for 1TEC in Figures 4(a), 4(c), 4(b), and 4(d), respectively.

Similarly, cases D_3 and F_4 of 1TEE also predict near maximal atmospheric mixing angle (θ_{23}) for IO (Figures 5(a) and 5(b)). Interestingly the parameter space of reactor mixing angle θ_{13} is found to be constrained between 0° and 35° (Figures 5(c) and 5(d)). In Figures 5(c) and 5(d), it is clear that, for the allowed experimental range of θ_{13} ($8.5^\circ - 9.8^\circ$), θ_{23} inches closer to 45° . Similar predictions have been noted for cases D_3 and F_4 of 1TEC, however, for normal mass ordering (NO) (Figures 6(a), 6(b), 6(c), and 6(d)).

3.2. Comparing the Results for 1TEE and 1TEC Texture Structures. In this subsection, we compare the results of all the viable structures of 1TEE and 1TEC in neutrino mass matrix. It is worthwhile to mention that the present refinements of the experimental data do not limit the number of viable cases in 1TEE and 1TEC textures respectively. The number of viable cases obtained is the same as predicted in [21, 26, 27] for 1TEE and 1TEC, respectively. For executing the analysis, we vary the allowed ranges of three neutrino mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and mass squared differences ($\delta m^2, \Delta m^2$) within their 3σ confidence level. To facilitate the comparison, we have encapsulated the the predictions regarding three CP violating phases (ρ, σ, δ) and neutrino masses $m_{1,2,3}$ for all the allowed texture structures of 1TEE and 1TEC, respectively (Tables 3, 4, 5, and 6).

Category A. In Category A, there are 10 possible cases out of which only four ($A_{1,4,5,6}$) are allowed for 1TEE at 3σ CL, and in addition inverted mass ordering (IO) is ruled out for all these cases. On the other hand, only three ($A_{1,4,6}$) are allowed

FIGURE 6: Correlation plots for textures D_3 ((a), (c)) and F_4 ((b), (d)) with NO for 1TEC at 3σ CL. The symbols have their usual meaning. In (a) and (b), colored horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e., $|M|_{ee} < 0.165$ eV) at 90 ($<2\sigma$)% CL, given in KamLAND experiment [7]. In (c) and (d), we have shown the upper limit on reactor mixing angle θ_{13} .

for 1TEC with current oscillation data, while normal mass ordering (NO) is ruled out for these cases. For 1TEE, ρ, σ, δ remain unconstrained; however, for 1TEC, only δ remains unconstrained, while Majorana phases (ρ, σ) are restricted near 0° pertaining to viable cases. From Table 3, it is clear that lower bound on lowest neutrino mass (m_1 (NO) or m_3 (IO)) is nearly equal or less than 1 meV for 1TEE and 1TEC.

Category B (C). In Category B, all the ten possible cases are allowed for both 1TEE and 1TEC, respectively, at 3σ CL; however, cases $B_{1,6,7}$ allow only NO for 1TEE, while the same allow only IO for 1TEC (Table 4). Cases $B_{2,3,4,5,8,9,10}$ allow both NO and IO for 1TEE and 1TEC, respectively. As mentioned in [26, 27], cases of Category B are related to the cases belonging to Category C through permutation symmetry; therefore, we can obtain the results for Category C from B. We find that cases $C_{1,2,3}$ allow only NO for 1TEE, while the same allow IO for 1TEC.

Textures B_1 (NO), B_3 (NO, IO), B_5 (NO, IO), B_6 (NO), B_7 (NO), B_8 (NO), B_{10} (NO), C_1 (NO), C_2 (NO), C_3 (NO), C_4

(NO, IO), C_6 (NO, IO), C_8 (NO), and C_{10} (NO) held nearly no constraint on Dirac CP violating phase (δ) for 1TEE and 1TEC, respectively, but with opposite neutrino mass ordering (Table 4). Only cases B_2 (NO), B_4 (IO), C_7 (NO), and C_5 (IO) for 1TEE and B_2 (IO), B_4 (NO), C_7 (IO), and C_5 (NO) for 1TEC show significant reduction in the parameter space of δ . It is found that δ is restricted near 90° and 270° for 1TEE and 1TEC, respectively (Table 4). These predictions are significant considering the latest hint on δ near 270° [5, 6]. Therefore all the above cases discussed are almost indistinguishable for 1TEE and 1TEC, if neutrino mass ordering is not considered.

Category D(F). All the ten possible cases belonging to Category D are acceptable with neutrino oscillation data at 3σ CL for 1TEE and 1TEC, respectively (Table 5). However cases $D_{1,2,4,5,6,7,9}$ favor both NO and IO for 1TEE and 1TEC, while D_3 , D_8 , and D_{10} are acceptable only for IO in case of 1TEE; however, the same cases allowed NO in case of 1TEC. Similarly, the results for cases belonging to Category F can be derived from Category D.

TABLE 2: Sixty phenomenologically possible hybrid texture structures of M_ν at 3σ C.L where the triangles “ Δ ” denote equal and nonzero elements (or cofactors) and “0” denotes the vanishing element (or minor). “ $\times$ ” denotes the nonzero elements or cofactor.

	A	B	C	D	E	F
1	$\begin{pmatrix} 0 & \Delta & \Delta \\ \Delta & \times & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & 0 & \Delta \\ 0 & \times & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \Delta & 0 \\ \Delta & \times & \times \\ 0 & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \Delta & \times \\ \Delta & 0 & \times \\ \times & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \Delta & \times \\ \Delta & \times & 0 \\ \times & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \Delta & \times \\ \Delta & \times & \times \\ \times & \times & 0 \end{pmatrix}$
2	$\begin{pmatrix} 0 & \Delta & \times \\ \Delta & \Delta & \times \\ \times & \times & \times \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \Delta \\ 0 & \Delta & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & 0 \\ \times & \Delta & \times \\ 0 & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \Delta \\ \times & 0 & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \Delta \\ \times & \times & 0 \\ \Delta & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \Delta \\ \times & \times & \times \\ \Delta & \times & 0 \end{pmatrix}$
3	$\begin{pmatrix} 0 & \times & \Delta \\ \times & \times & \Delta \\ \Delta & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \Delta \\ 0 & \times & \Delta \\ \Delta & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & 0 \\ \times & \times & \Delta \\ 0 & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & 0 \\ \times & 0 & \Delta \\ 0 & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \times \\ \times & \Delta & 0 \\ \times & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \times \\ \times & \Delta & \times \\ \times & \times & 0 \end{pmatrix}$
4	$\begin{pmatrix} 0 & \times & \times \\ \times & \Delta & \Delta \\ \times & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \Delta \\ 0 & \times & \times \\ \Delta & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & 0 \\ \times & \times & \times \\ 0 & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \times \\ \times & 0 & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \times \\ \times & \times & 0 \\ \times & 0 & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & \times & \times \\ \times & \times & \Delta \\ \times & \Delta & 0 \end{pmatrix}$
5	$\begin{pmatrix} 0 & \times & \times \\ \times & \Delta & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & 0 & \times \\ 0 & \Delta & \times \\ \times & \times & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & 0 \\ \Delta & \Delta & \times \\ 0 & \times & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \Delta \\ \Delta & 0 & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \Delta \\ \Delta & \times & 0 \\ \Delta & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \Delta \\ \Delta & \times & \times \\ \Delta & \times & 0 \end{pmatrix}$
6	$\begin{pmatrix} 0 & \times & \times \\ \times & \times & \Delta \\ \times & \Delta & \Delta \end{pmatrix}$	$\begin{pmatrix} \Delta & 0 & \times \\ 0 & \times & \Delta \\ \times & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & 0 \\ \Delta & \times & \Delta \\ 0 & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & 0 & \Delta \\ \times & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & \Delta & 0 \\ \times & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & \Delta & \times \\ \times & \times & 0 \end{pmatrix}$
7	$\begin{pmatrix} 0 & \Delta & \times \\ \Delta & \times & \Delta \\ \times & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \Delta & 0 & \times \\ 0 & \times & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & 0 \\ \Delta & \times & \times \\ 0 & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & 0 & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & \times & 0 \\ \times & 0 & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \Delta & \times \\ \Delta & \times & \Delta \\ \times & \Delta & 0 \end{pmatrix}$
8	$\begin{pmatrix} 0 & \times & \Delta \\ \times & \times & \times \\ \Delta & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \times \\ 0 & \Delta & \Delta \\ \times & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & 0 \\ \times & \Delta & \Delta \\ 0 & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & 0 & \Delta \\ \Delta & \Delta & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & \Delta & 0 \\ \Delta & 0 & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & \Delta & \times \\ \Delta & \times & 0 \end{pmatrix}$
9	$\begin{pmatrix} 0 & \times & \Delta \\ \times & \Delta & \times \\ \Delta & \times & \times \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \times \\ 0 & \Delta & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & 0 \\ \times & \Delta & \times \\ 0 & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & 0 & \times \\ \Delta & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & \times & 0 \\ \Delta & 0 & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \Delta \\ \times & \times & \Delta \\ \Delta & \Delta & 0 \end{pmatrix}$
10	$\begin{pmatrix} 0 & \Delta & \times \\ \Delta & \times & \times \\ \times & \times & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & 0 & \times \\ 0 & \times & \Delta \\ \times & \Delta & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \Delta \\ 0 & \Delta & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & \Delta \\ \times & \Delta & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \times \\ \times & \Delta & 0 \\ \times & 0 & \Delta \end{pmatrix}$	$\begin{pmatrix} \times & \times & \times \\ \times & \Delta & \Delta \\ \times & \Delta & 0 \end{pmatrix}$

Cases D_1 (IO), D_2 (IO), D_3 (IO), D_4 (IO), D_5 (NO, IO), D_6 (IO), D_7 (NO, IO), D_8 (IO), D_9 (NO, IO), D_{10} (IO), F_1 (IO), F_2 (IO), F_3 (IO), F_4 (IO), F_5 (NO, IO), F_6 (IO), F_7 (NO, IO), F_8 (IO), F_9 (NO, IO), and F_{10} (IO) predict literally no constraints on δ for 1TEE. These cases give identical predictions for 1TEC, but for opposite mass ordering. For cases D_1 (NO), D_2 (NO), D_4 (NO), D_6 (NO), F_1 (NO),

F_2 (NO), F_4 (NO), and F_6 (NO), the parameter space of δ is found to be well constrained for 1TEE. These cases give similar predictions regarding the parameter space of δ for 1TEC, but for IO.

Category E. In Category E, all the ten possible cases are allowed for 1TEE at 3σ CL, while only nine other than E_5 are

TABLE 3: The allowed ranges of Dirac CP-violating phase δ , the Majorana phases ρ , σ , and three neutrino masses m_1 , m_2 , m_3 for the experimentally allowed cases of Category A. Masses are in eV. “ $\times$ ” denotes the nonviability of case for a particular mass ordering.

Cases	ITEE		ITEC	
	NO	IO	NO	IO
A_1	$\rho = -90^\circ - 90^\circ$	$\times$	$\times$	$\rho = -0.0277^\circ - -0.0220^\circ \oplus 0.0214^\circ - 0.0274^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\times$	$\times$	$\sigma = -0.0273^\circ - 0.0271^\circ$
	$\delta = 0^\circ - 360^\circ$	$\times$	$\times$	$\delta = 0^\circ - 360^\circ$
	$m_1 = 0.00147 - 0.0106$	$\times$	$\times$	$m_1 = 0.0430 - 0.0534$
	$m_2 = 0.00849 - 0.0139$	$\times$	$\times$	$m_2 = 0.0439 - 0.0541$
	$m_3 = 0.0437 - 0.0551$	$\times$	$\times$	$m_3 = 0.000904 - 0.00504$
$A_2 (A_8)$	$\times$	$\times$	$\times$	$\times$
$A_3 (A_7)$	$\times$	$\times$	$\times$	$\times$
$A_4 (A_6)$	$\rho = -90^\circ - 90^\circ$	$\times$	$\times$	$\rho = -0.0275^\circ - -0.0222^\circ \oplus 0.0215^\circ - 0.0269^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\times$	$\times$	$\sigma = -0.0250^\circ - 0.0268^\circ$
	$\delta = 0^\circ - 360^\circ$	$\times$	$\times$	$\delta = 0^\circ - 360^\circ$
	$m_1 = 0.00148 - 0.0106$	$\times$	$\times$	$m_1 = 0.0431 - 0.0534$
	$m_2 = 0.00850 - 0.0139$	$\times$	$\times$	$m_2 = 0.0439 - 0.0540$
	$m_3 = 0.0437 - 0.0551$	$\times$	$\times$	$m_3 = 0.000950 - 0.00504$
$A_5 (A_5)$	$\rho = -90^\circ - 90^\circ$	$\times$	$\times$	$\times$
	$\sigma = -90^\circ - 90^\circ$	$\times$	$\times$	$\times$
	$\delta = 0^\circ - 360^\circ$	$\times$	$\times$	$\times$
	$m_1 = 0.00163 - 0.0105$	$\times$	$\times$	$\times$
	$m_2 = 0.00854 - 0.0137$	$\times$	$\times$	$\times$
	$m_3 = 0.0438 - 0.0545$	$\times$	$\times$	$\times$
$A_9 (A_{10})$	$\times$	$\times$	$\times$	$\times$

acceptable in case of ITEC (Table 6). Cases $E_{1,2,3,4,6,7,8,9}$ allow only inverted mass ordering (IO) for ITEE, while the same textures allow only normal mass ordering (NO) for ITEC. Cases E_5 and E_{10} allow both NO and IO for ITEE; however E_5 is ruled out for both NO and IO for ITEC at 3σ CL. Similar to cases belonging to Category D, $E_{1,2,3,4,5,6,7,8,9}$ (IO) cover full range of ρ, σ, δ for ITEE, whereas the same cases (except E_5) give identical predictions for ITEC, but for NO. For E_5 (NO) and E_{10} (NO), phases ρ, σ, δ are somewhat restricted at 3σ CL for ITEE, while only for E_{10} (IO), the parameter space of ρ, σ, δ seems to be restricted for ITEC (Table 6).

To summarize our discussion, we have investigated all the viable cases of ITEE and ITEC texture structures in the limit of large effective neutrino mass $|M|_{ee}$. It is found that only four cases are able to produce near maximal atmospheric mixing for ITEE and ITEC, respectively. However, the predictions remain true irrespective of the experimental data on solar and reactor mixing angle. The observation also hints towards the indistinguishable feature of ITEE and ITEC texture structures, but for opposite mass ordering. In order to depict the indistinguishability, we have carried out a comparative study of ITEE and ITEC texture structures using the current experimental data at 3σ CL. From our discussion we find that most of the cases belonging to ITEE and ITEC

are almost indistinguishable as far as the neutrino oscillation parameters are concerned, but with opposite neutrino mass ordering. The indistinguishable nature of ITEE and ITEC is more prominent for quasi-degenerate mass ordering. For the cases where lower bound on lowest neutrino mass is very small (<1 meV), there is noticeable deviation in the predictions for ITEE and ITEC (Tables 3, 4, 5, and 6). This point is also discussed by Liao et. al. in [31]. In addition, the parameter space of δ for most of the cases belonging to ITEE and ITEC remains unrestricted, while only eight cases show maximal restriction for δ . Since no presently feasible experiment has been able to determine the neutrino mass ordering, therefore, we cannot distinguish ITEE and ITEC structures using the present oscillation data. However, the currently running and forthcoming neutrino experiments aimed at distinguishing the mass ordering of neutrinos will test our phenomenological results. Also the ongoing and future neutrino-less double beta decay experiments are capable of measuring $|M|_{ee}$ term, which would, in turn, either confirm or rule out our assumption of large $|M|_{ee}$.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

TABLE 4: The allowed ranges of Dirac CP-violating phase δ , the Majorana phases ρ , σ , and three neutrino masses m_1 , m_2 , m_3 for the experimentally allowed cases of Category B (C). Masses are in eV. “ $\times$ ” denotes the nonviability of case for a particular mass ordering.

Cases	ITEE		ITEC	
	NO	IO	NO	IO
B_1 (C_1)	$\rho = -90^\circ - 90^\circ$	$\times$	$\times$	$\rho = -0.0277^\circ - 0.0279^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\times$	$\times$	$\sigma = -0.0284^\circ - 0.0284^\circ$
	$\delta = 0^\circ - 360^\circ$	$\times$	$\times$	$\delta = 0^\circ - 360^\circ$
	$m_1 = 0.00550 - 0.0298$	$\times$	$\times$	$m_1 = 0.0439 - 0.0597$
	$m_2 = 0.0101 - 0.0310$	$\times$	$\times$	$m_2 = 0.0447 - 0.0604$
B_2 (C_7)	$m_3 = 0.0443 - 0.0605$	$\times$	$\times$	$m_3 = 0.000754 - 0.0297$
	$\rho = -2.76^\circ - 2.81^\circ$	$\rho = -7.74^\circ - 7.75^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -4.46^\circ - 4.40^\circ$
	$\sigma = -10.48^\circ - 10.22^\circ$	$\sigma = -8.84^\circ - 9.22^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -5.41^\circ - 5.39^\circ$
	$\delta = 77.3^\circ - 94.2^\circ \oplus 266.3^\circ - 284^\circ$	$\delta = 84.01^\circ - 98.7^\circ \oplus 262.19^\circ - 276.6^\circ$	$\delta = 86.22^\circ - 273.3^\circ$	$\delta = 81.56^\circ - 96.48^\circ \oplus 263.7^\circ - 278.4^\circ$
	$m_1 = 0.0235 - 0.314$	$m_1 = 0.0453 - 0.277$	$m_1 = 0.00548 - 0.267$	$m_1 = 0.0507 - 0.419$
B_3 (C_6)	$m_2 = 0.0242 - 0.0310$	$m_2 = 0.0465 - 0.274$	$m_2 = 0.00806 - 0.316$	$m_2 = 0.0508 - 0.419$
	$m_3 = 0.0485 - 0.0315$	$m_3 = 0.0117 - 0.271$	$m_3 = 0.0428 - 0.320$	$m_3 = 0.0249 - 0.414$
	$\rho = -90^\circ - -5.9^\circ \oplus 5.9^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$
	$\sigma = -90^\circ - -5.9^\circ \oplus 5.9^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$
	$\delta = 7.47^\circ - 356^\circ$	$\delta = 8.3^\circ - 173^\circ \oplus 187^\circ - 351^\circ$	$\delta = 5.16^\circ - 178^\circ \oplus 183.7^\circ - 353.6^\circ$	$\delta = 0^\circ - 360^\circ$
B_4 (C_5)	$m_1 = 0.0153 - 0.331$	$m_1 = 0.0459 - 0.335$	$m_1 = 0.00504 - 0.485$	$m_1 = 0.0427 - 0.505$
	$m_2 = 0.0161 - 0.331$	$m_2 = 0.0461 - 0.334$	$m_2 = 0.00920 - 0.483$	$m_2 = 0.0445 - 0.503$
	$m_3 = 0.0445 - 0.0335$	$m_3 = 0.0136 - 0.330$	$m_3 = 0.0416 - 0.480$	$m_3 = 0.00884 - 0.500$
	$\rho = -19.07^\circ - 19.75^\circ$	$\rho = -4.80^\circ - 4.66^\circ$	$\rho = -43.13^\circ - 40.12^\circ$	$\rho = -16.38^\circ - 18.8^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\sigma = -2.83^\circ - 3.12^\circ$	$\sigma = -43^\circ - 40.1^\circ$	$\sigma = -41.43^\circ - 40.59^\circ$
B_5 (C_4)	$\delta = 0^\circ - 100^\circ \oplus 260.2^\circ - 360^\circ$	$\delta = 84.68^\circ - 94.7^\circ \oplus 265.08^\circ - 275.5^\circ$	$\delta = 88.04^\circ - 124.4^\circ \oplus 230.09^\circ - 272^\circ$	$\delta = 5.56^\circ - 13.82^\circ \oplus 255.7^\circ - 307.3^\circ$
	$m_1 = 0.00681 - 0.318$	$m_1 = 0.0488 - 0.314$	$m_1 = 0.0105 - 0.373$	$m_1 = 0.0444 - 0.420$
	$m_2 = 0.00969 - 0.0317$	$m_2 = 0.0486 - 0.312$	$m_2 = 0.0129 - 0.369$	$m_2 = 0.0447 - 0.416$
	$m_3 = 0.0421 - 0.0321$	$m_3 = 0.0202 - 0.310$	$m_3 = 0.0435 - 0.374$	$m_3 = 0.0103 - 0.418$
	$\rho = -20.83^\circ - 20.79^\circ$	$\rho = -90^\circ - -11.3^\circ \oplus 11.3^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -24.19^\circ - 24.45^\circ$
B_6 (C_3)	$\sigma = -36.3^\circ - 36^\circ$	$\sigma = -90^\circ - -14.3^\circ \oplus 14.8^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -27.7^\circ - 27.4^\circ$
	$\delta = 0^\circ - 177.5^\circ \oplus 182^\circ - 360^\circ$	$\delta = 0^\circ - 168^\circ \oplus 192.5^\circ - 360^\circ$	$\delta = 9.33^\circ - 172.4^\circ \oplus 187.20^\circ - 350.4^\circ$	$\delta = 0^\circ - 179.3^\circ \oplus 180.6^\circ - 360^\circ$
	$m_1 = 0.00965 - 0.330$	$m_1 = 0.0761 - 0.330$	$m_1 = 0.0603 - 0.498$	$m_1 = 0.0440 - 0.498$
	$m_2 = 0.0113 - 0.0330$	$m_2 = 0.0762 - 0.330$	$m_2 = 0.0608 - 0.496$	$m_2 = 0.0447 - 0.499$
	$m_3 = 0.0421 - 0.0332$	$m_3 = 0.0603 - 0.328$	$m_3 = 0.0629 - 0.500$	$m_3 = 0.0103 - 0.499$
B_6 (C_3)	$\rho = -90^\circ - 90^\circ$	$\times$	$\times$	$\rho = -90^\circ - 90^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\times$	$\times$	$\sigma = -90^\circ - 90^\circ$
	$\delta = 0^\circ - 360^\circ$	$\times$	$\times$	$\delta = 0^\circ - 360^\circ$
	$m_1 = 0.0147 - 0.324$	$\times$	$\times$	$m_1 = 0.0452 - 0.454$
	$m_2 = 0.00161 - 0.324$	$\times$	$\times$	$m_2 = 0.0451 - 0.451$
B_6 (C_3)	$m_3 = 0.0445 - 0.324$	$\times$	$\times$	$m_3 = 0.00161 - 0.450$

TABLE 4: Continued.

Cases	ITEE		ITEC	
	NO	IO	NO	IO
B_7 (C_2)	$\rho = -26.25^0 - 26.43^0$	$\times$	$\times$	$\rho = -30.92^0 - 30.42^0$
	$\sigma = -50.28^0 - 50.2^0$	$\times$	$\times$	$\sigma = -41.9^0 - 43.8^0$
	$\delta = 0^0 - 177.5^0 \oplus 182^0 - 360^0$	$\times$	$\times$	$\delta = 0^0 - 360^0$
	$m_1 = 0.00883 - 0.331$	$\times$	$\times$	$m_1 = 0.0447 - 0.498$
	$m_2 = 0.00121 - 0.329$	$\times$	$\times$	$m_2 = 0.0451 - 0.498$
B_8 (C_{10})	$m_3 = 0.0421 - 0.334$	$\times$	$\times$	$m_3 = 0.00804 - 0.498$
	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$
	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$
	$\delta = 0^0 - 166.5^0 \oplus 196.5^0 - 360^0$	$\delta = 45.05^0 - 135^0 \oplus 224.5^0 - 314.6^0$	$\delta = 45.86^0 - 315.05^0$	$\delta = 0^0 - 360^0$
	$m_1 = 0.00127 - 0.279$	$m_1 = 0.0418 - 0.279$	$m_1 = 0.00498 - 0.381$	$m_1 = 0.0427 - 0.303$
B_9 (C_9)	$m_2 = 0.00691 - 0.277$	$m_2 = 0.0429 - 0.307$	$m_2 = 0.00736 - 0.382$	$m_2 = 0.0428 - 0.302$
	$m_3 = 0.0409 - 0.280$	$m_3 = 0.00398 - 0.305$	$m_3 = 0.0407 - 0.384$	$m_3 = 0.00342 - 0.298$
	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$
	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$
	$\delta = 5.55^0 - 354^0$	$\delta = 12^0 - 171.7^0 \oplus 189.7^0 - 352.7^0$	$\delta = 8.32^0 - 175.9^0 \oplus 186^0 - 350.47^0$	$\delta = 0^0 - 360^0$
B_{10} (C_8)	$m_1 = 0.00338 - 0.279$	$m_1 = 0.0435 - 0.319$	$m_1 = 0.00622 - 0.487$	$m_1 = 0.0447 - 0.486$
	$m_2 = 0.00831 - 0.277$	$m_2 = 0.0445 - 0.319$	$m_2 = 0.00681 - 0.486$	$m_2 = 0.0451 - 0.487$
	$m_3 = 0.0423 - 0.282$	$m_3 = 0.00398 - 0.317$	$m_3 = 0.00914 - 0.486$	$m_3 = 0.00458 - 0.480$
	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$	$\rho = -90^0 - 90^0$
	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$	$\sigma = -90^0 - 90^0$
B_{10} (C_8)	$\delta = 0^0 - 360^0$	$\delta = 44.64^0 - 136.5^0 \oplus 224.6^0 - 314.2^0$	$\delta = 1.92^0 - 313.04^0$	$\delta = 0^0 - 360^0$
	$m_1 = 0.00163 - 0.294$	$m_1 = 0.0425 - 0.277$	$m_1 = 0.00516 - 0.348$	$m_1 = 0.0427 - 0.365$
	$m_2 = 0.00691 - 0.293$	$m_2 = 0.0423 - 0.275$	$m_2 = 0.00806 - 0.346$	$m_2 = 0.0453 - 0.365$
	$m_3 = 0.0409 - 0.299$	$m_3 = 0.00380 - 0.272$	$m_3 = 0.0416 - 0.348$	$m_3 = 0.00879 - 0.391$

TABLE 5: The allowed ranges of Dirac CP-violating phase δ , the Majorana phases ρ , σ , and three neutrino masses m_1 , m_2 , m_3 for the experimentally allowed cases of Category D (F). Masses are in eV. “ $\times$ ” denotes the nonviability of case for a particular mass ordering.

Cases	ITEE			ITEC		
	NO	IO	IO	NO	IO	IO
$D_1 (F_2)$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$
	$\delta = 30.185^\circ - 322.6^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 31.79^\circ - 318.66^\circ$
	$m_1 = 0.0541 - 0.224$	$m_1 = 0.00432 - 0.252$	$m_1 = 0.00432 - 0.252$	$m_1 = 0.00331 - 0.603$	$m_1 = 0.00331 - 0.603$	$m_1 = 0.0731 - 0.501$
	$m_2 = 0.0538 - 0.224$	$m_2 = 0.00437 - 0.251$	$m_2 = 0.00437 - 0.251$	$m_2 = 0.00800 - 0.606$	$m_2 = 0.00800 - 0.606$	$m_2 = 0.0719 - 0.500$
$D_2 (F_1)$	$m_3 = 0.0679 - 0.230$	$m_3 = 0.00343 - 0.248$	$m_3 = 0.00343 - 0.248$	$m_3 = 0.0371 - 0.604$	$m_3 = 0.0371 - 0.604$	$m_3 = 0.0593 - 0.496$
	$\rho = -50.28^\circ - 60.48^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -63.3^\circ - 64^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -89.37^\circ - 86.25^\circ$
	$\delta = 87.19^\circ - 297.4^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 64.34^\circ \oplus 295.7^\circ - 360^\circ$	$\delta = 0^\circ - 64.34^\circ \oplus 295.7^\circ - 360^\circ$	$\delta = 70.50^\circ - 295.77^\circ$
	$m_1 = 0.124 - 0.293$	$m_1 = 0.0422 - 0.263$	$m_1 = 0.0422 - 0.263$	$m_1 = 0.00542 - 0.0277$	$m_1 = 0.00542 - 0.0277$	$m_1 = 0.128 - 0.581$
$D_3 (F_4)$	$m_2 = 0.125 - 0.294$	$m_2 = 0.0430 - 0.262$	$m_2 = 0.0430 - 0.262$	$m_2 = 0.00993 - 0.0291$	$m_2 = 0.00993 - 0.0291$	$m_2 = 0.130 - 0.582$
	$m_3 = 0.132 - 0.295$	$m_3 = 0.00552 - 0.257$	$m_3 = 0.00552 - 0.257$	$m_3 = 0.0440 - 0.0600$	$m_3 = 0.0440 - 0.0600$	$m_3 = 0.120 - 0.579$
	$\times$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\times$
	$\times$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\times$
	$\times$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 64.34^\circ \oplus 295.7^\circ - 360^\circ$	$\delta = 0^\circ - 64.34^\circ \oplus 295.7^\circ - 360^\circ$	$\times$
$D_4 (F_3)$	$\times$	$m_1 = 0.0439 - 0.308$	$m_1 = 0.0439 - 0.308$	$m_1 = 0.0161 - 0.474$	$m_1 = 0.0161 - 0.474$	$\times$
	$\times$	$m_2 = 0.0445 - 0.308$	$m_2 = 0.0445 - 0.308$	$m_2 = 0.0164 - 0.471$	$m_2 = 0.0164 - 0.471$	$\times$
	$\times$	$m_3 = 0.00888 - 0.304$	$m_3 = 0.00888 - 0.304$	$m_3 = 0.0416 - 0.469$	$m_3 = 0.0416 - 0.469$	$\times$
	$\rho = -58.71^\circ - 59.35^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -61.4^\circ - 61.5^\circ$
	$\sigma = -88.90^\circ - 87.18^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$
$D_5 (F_5)$	$\delta = 75.87^\circ - 285.58^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 18.12^\circ - 318.75^\circ$	$\delta = 18.12^\circ - 318.75^\circ$	$\delta = 77.86^\circ - 286.15^\circ$
	$m_1 = 0.0574 - 0.287$	$m_1 = 0.00429 - 0.254$	$m_1 = 0.00429 - 0.254$	$m_1 = 0.0102 - 0.795$	$m_1 = 0.0102 - 0.795$	$m_1 = 0.0711 - 0.424$
	$m_2 = 0.0575 - 0.286$	$m_2 = 0.00430 - 0.254$	$m_2 = 0.00430 - 0.254$	$m_2 = 0.0147 - 0.796$	$m_2 = 0.0147 - 0.796$	$m_2 = 0.0740 - 0.424$
	$m_3 = 0.0679 - 0.291$	$m_3 = 0.00969 - 0.202$	$m_3 = 0.00969 - 0.202$	$m_3 = 0.0369 - 0.790$	$m_3 = 0.0369 - 0.790$	$m_3 = 0.0564 - 0.418$
	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$
$D_6 (F_6)$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$
	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$
	$m_1 = 0.0337 - 0.334$	$m_1 = 0.0431 - 0.335$	$m_1 = 0.0431 - 0.335$	$m_1 = 0.00255 - 0.509$	$m_1 = 0.00255 - 0.509$	$m_1 = 0.0538 - 0.505$
	$m_2 = 0.0338 - 0.334$	$m_2 = 0.0434 - 0.334$	$m_2 = 0.0434 - 0.334$	$m_2 = 0.00370 - 0.505$	$m_2 = 0.00370 - 0.505$	$m_2 = 0.0539 - 0.506$
	$m_3 = 0.0541 - 0.334$	$m_3 = 0.00940 - 0.330$	$m_3 = 0.00940 - 0.330$	$m_3 = 0.0351 - 0.510$	$m_3 = 0.0351 - 0.510$	$m_3 = 0.0305 - 0.500$
$D_7 (F_7)$	$\rho = -65.09^\circ - 58.48^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -90^\circ - 90^\circ$	$\rho = -23.03^\circ - 7.74^\circ \oplus 7.66^\circ - 22.14^\circ$	$\rho = -18.42^\circ - 6.56^\circ \oplus 6.77^\circ - 18.27^\circ$	$\rho = -18.42^\circ - 6.56^\circ \oplus 6.77^\circ - 18.27^\circ$
	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -90^\circ - 90^\circ$	$\sigma = -68.53^\circ - 38.75^\circ \oplus 37.86^\circ - 69.0^\circ$	$\sigma = -71.1^\circ - 46.2^\circ \oplus 46.2^\circ - 70.48^\circ$	$\sigma = -71.1^\circ - 46.2^\circ \oplus 46.2^\circ - 70.48^\circ$
	$\delta = 64.2^\circ - 288.1^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 0^\circ - 360^\circ$	$\delta = 109.68^\circ - 150.05^\circ \oplus 210.4^\circ - 250.2^\circ$	$\delta = 118.19^\circ - 154.2^\circ \oplus 206.7^\circ - 242.3^\circ$	$\delta = 118.19^\circ - 154.2^\circ \oplus 206.7^\circ - 242.3^\circ$
	$m_1 = 0.0974 - 0.323$	$m_1 = 0.0446 - 0.277$	$m_1 = 0.0446 - 0.277$	$m_1 = 0.0202 - 0.456$	$m_1 = 0.0202 - 0.456$	$m_1 = 0.108 - 0.398$
	$m_2 = 0.0965 - 0.0321$	$m_2 = 0.0448 - 0.277$	$m_2 = 0.0448 - 0.277$	$m_2 = 0.0204 - 0.456$	$m_2 = 0.0204 - 0.456$	$m_2 = 0.109 - 0.396$
$D_8 (F_8)$	$m_3 = 0.107 - 0.0326$	$m_3 = 0.00888 - 0.324$	$m_3 = 0.00888 - 0.324$	$m_3 = 0.0451 - 0.456$	$m_3 = 0.0451 - 0.456$	$m_3 = 0.0962 - 0.396$

TABLE 5: Continued.

Cases	ITEE		ITEC	
	NO	IO	NO	IO
$D_7 (F_8)$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$
	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$
	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$
	$m_1 = 0.0478-0.273$	$m_1 = 0.0439-0.333$	$m_1 = 0.00663-0.436$	$m_1 = 0.0647-0.437$
	$m_2 = 0.0479-0.273$	$m_2 = 0.0454-0.333$	$m_2 = 0.0103-0.434$	$m_2 = 0.0649-0.438$
$D_8 (F_7)$	$m_3 = 0.0644-0.300$	$m_3 = 0.00806-0.330$	$m_3 = 0.0416-0.438$	$m_3 = 0.0439-0.491$
	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-64.34^0 \oplus 295.7^0-360^0$	$\times$
	$\times$	$m_1 = 0.0451-0.0938$	$m_1 = 0.00941-0.0803$	$\times$
$D_9 (F_6)$	$\times$	$m_2 = 0.0459-0.0941$	$m_2 = 0.0125-0.0804$	$\times$
	$\times$	$m_3 = 0.00121-0.0790$	$m_3 = 0.0445-0.0953$	$\times$
	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$
	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$
	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$
$D_{10} (F_{10})$	$m_1 = 0.0492-0.300$	$m_1 = 0.0455-0.310$	$m_1 = 0.00769-0.436$	$m_1 = 0.0647-0.411$
	$m_2 = 0.0496-0.300$	$m_2 = 0.0456-0.310$	$m_2 = 0.00932-0.434$	$m_2 = 0.0638-0.412$
	$m_3 = 0.0638-0.303$	$m_3 = 0.00969-0.306$	$m_3 = 0.0426-0.438$	$m_3 = 0.0458-0.407$
	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
$D_{10} (F_{10})$	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-64.34^0 \oplus 295.7^0-360^0$	$\times$
	$\times$	$m_1 = 0.0432-0.102$	$m_1 = 0.00201-0.0793$	$\times$
	$\times$	$m_2 = 0.0442-0.102$	$m_2 = 0.00870-0.0795$	$\times$
	$\times$	$m_3 = 0.00301-0.0901$	$m_3 = 0.0435-0.0932$	$\times$
	$\times$			

TABLE 6: The allowed ranges of Dirac CP-violating phase δ , the Majorana phases ρ , σ , and three neutrino masses m_1 , m_2 , m_3 for the experimentally allowed cases of Category E. Masses are in eV. “x” denotes the nonviability of case for a particular mass ordering.

Cases	ITTE		ITEC	
	NO	IO	NO	IO
E_1 (E_2)	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-64.34^0 \oplus 295.7^0-360^0$	$\times$
	$\times$	$m_1 = 0.0511-0.0804$	$m_1 = 0.00283-0.0629$	$\times$
	$\times$	$m_2 = 0.0516-0.0805$	$m_2 = 0.00878-0.0634$	$\times$
E_3 (E_4)	$\times$	$m_3 = 0.0264-0.0678$	$m_3 = 0.0440-0.0809$	$\times$
	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-64.34^0 \oplus 295.7^0-360^0$	$\times$
	$\times$	$m_1 = 0.0439-0.333$	$m_1 = 0.00914-0.499$	$\times$
E_5	$\times$	$m_2 = 0.0457-0.333$	$m_2 = 0.00115-0.504$	$\times$
	$\times$	$m_3 = 0.00888-0.333$	$m_3 = 0.0432-0.500$	$\times$
	$\rho = -90^0--156 \oplus 29.3-90^0$	$\rho = -90^0-90^0$	$\times$	$\times$
	$\rho = -90^0--156 \oplus 29.3-90^0$	$\sigma = -90^0-90^0$	$\times$	$\times$
	$\delta = 29.3^0-153.5^0 \oplus 206.5^0-334^0$	$\delta = 0^0-360^0$	$\times$	$\times$
E_6 (E_9)	$m_1 = 0.130-0.332$	$m_1 = 0.0439-0.269$	$\times$	$\times$
	$m_2 = 0.132-0.330$	$m_2 = 0.0451-0.270$	$\times$	$\times$
	$m_3 = 0.137-0.334$	$m_3 = 0.0103-0.262$	$\times$	$\times$
	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
E_7 (E_8)	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\times$
	$\times$	$m_1 = 0.0511-0.333$	$m_1 = 0.00914-0.499$	$\times$
	$\times$	$m_2 = 0.0517-0.333$	$m_2 = 0.00115-0.504$	$\times$
	$\times$	$m_3 = 0.0273-0.333$	$m_3 = 0.0432-0.500$	$\times$
	$\times$	$\rho = -90^0-90^0$	$\rho = -90^0-90^0$	$\times$
E_{10}	$\times$	$\sigma = -90^0-90^0$	$\sigma = -90^0-90^0$	$\times$
	$\times$	$\delta = 0^0-360^0$	$\delta = 0^0-360^0$	$\times$
	$\times$	$m_1 = 0.0511-0.0908$	$m_1 = 0.0225-0.0469$	$\times$
	$\times$	$m_2 = 0.0517-0.0911$	$m_2 = 0.0238-0.0480$	$\times$
	$\times$	$m_3 = 0.0273-0.0746$	$m_3 = 0.0494-0.0708$	$\times$
E_{10}	$\rho = -90^0--28.6^0 \oplus 26.01^0-90^0$	$\rho = -18.15^0-18.08^0$	$\rho = -90^0-90^0$	$\rho = -90^0--19^0 \oplus 19.5^0-90^0$
	$\sigma = -90^0--28.6^0 \oplus 26.01^0-90^0$	$\sigma = -90^0--6.41^0 \oplus 6.09^0-90^0$	$\sigma = -90^0-90^0$	$\sigma = -90^0--19^0 \oplus 19.5^0-90^0$
	$\delta = 25.35^0-151.92^0 \oplus 206.97^0-332.3^0$	$\delta = 0^0-177^0 \oplus 184.3^0-357.5^0$	$\delta = 0^0-360^0$	$\delta = 23.75^0-161.97^0 \oplus 198.9^0-339^0$
	$m_1 = 0.136-0.331$	$m_1 = 0.0431-0.334$	$m_1 = 0.00156-0.481$	$m_1 = 0.141-0.481$
	$m_2 = 0.137-0.331$	$m_2 = 0.0445-0.334$	$m_2 = 0.00571-0.480$	$m_2 = 0.142-0.492$
E_{10}	$m_3 = 0.143-0.334$	$m_3 = 0.00969-0.330$	$m_3 = 0.0404-0.484$	$m_3 = 0.133-0.491$

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