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The Fourth SM Family, Breaking of Mass Democracy and the CKM Mixings

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Abstract

We consider violation of the democratic mass matrix in the framework of four family Standard Model. Predictions of fourth fermion masses as well as quark and lepton CKM mixings are presented.

In our previous article [1], we have argued that democratic mass matrix (DMM) approach [2-6] leads to the idea of existence of the fourth fermion family in the Standard Model. Here, we consider violations of full democracy which give possibility to obtain non-zero masses for the first three family fermions and to estimate the CKM mixings.

Let us repeat main arguments of the Ref.[1]. Before the symmetry breaking, fermions with the same quantum numbers (electric charge, weak isospin etc.) are indistinguishable. Therefore, in the fermion-Higgs interaction the Lagrangian terms corresponding to fermions with the same quantum numbers should come with equal strength. Consequently, after the spontaneous symmetry breaking one deals with singular mass matrices in which all entries are equal to $a\eta$, where a is the strength of fermion-Higgs interaction and η is the vacuum expectation value of the Higgs field. It seems natural to take a equal to the $SU(2)$ gauge coupling constant g . According to this approach, in the case of n SM families, $(n-1)$ families are massless and the n 'th family fermions have masses $ng\eta$. Taking the real mass spectrum of the third family fermions into account necessarily leads to the assumption that at least a fourth family must exist. In this case DMM approach leads to

$$M^0 = g\eta \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \rightarrow M = 4g\eta \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

for all types of fundametal fermions. As can be seen, the first three families remain massless and the fourth family fermion accept masses $4g\eta = 8m_W = 640$ GeV.

In nature, at least charged leptons and quarks from the first three families have non-zero masses which means that Eq.(1) needs an appropriate modification. Assuming a modification which has minimum effect on full democracy, we propose the following form of DMM

$$\begin{pmatrix} 1 & 1+\gamma & 1+\beta+\gamma & 1+\alpha-\beta-\gamma \\ 1+\gamma & 1+2\gamma & 1+\beta-\gamma & 1+\alpha-\beta-\gamma \\ 1+\beta+\gamma & 1+\beta-\gamma & 1+3\beta & 1+\alpha+2\beta+2\gamma \\ 1+\alpha-\beta-\gamma & 1+\alpha-\beta-\gamma & 1+\alpha+2\beta+2\gamma & 1+4\alpha \end{pmatrix} \quad (2)$$

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which is inspired by Fritzsch matrix written for the three family case [5]. Eigenvalues of matrix (2) give us masses of corresponding fermions which are used to fix the values of parameters α , β and γ . In Table 1 we present these values for up and down quark sector with predicted values of the fourth quark masses.

CKM matrix without phases is given as $O_{CKM} = O_u O_d^T$ where O_u and O_d are (real) rotations which diagonalize up and down quarks mass matrices respectively. With the parameters given in Table 1, one obtains

$$O_{CKM} = \begin{pmatrix} 0.9754 & 0.2201 & 0.0028 & 0.0001 \\ -0.2197 & 0.9743 & -0.0477 & -0.0011 \\ -0.0127 & 0.0441 & 0.9520 & 0.3024 \\ 0.0037 & -0.0128 & -0.3021 & 0.9531 \end{pmatrix} \quad (3)$$

This matrix should be compared with the experimental one

$$\begin{pmatrix} 0.9728 \text{ to } 0.9757 & 0.218 \text{ to } 0.224 & 0.002 \text{ to } 0.005 & . \\ 0.180 \text{ to } 0.228 & 0.800 \text{ to } 0.975 & 0.032 \text{ to } 0.048 & . \\ 0. \text{ to } 0.13 & 0. \text{ to } 0.56 & 0. \text{ to } 0.9995 & . \end{pmatrix} \quad (4)$$

taken from PDG [7]. As can be seen, our predictions are in good agreement with experimental data.

In the leptonic sector, we know masses of charged leptons precisely but for neutrino masses and mixings experiments give only upper limits. For these reasons, we have considered two different propositions for neutrino masses: (i) $m_{\nu_i} \sim m_{l_i}$ and (ii) $m_{\nu_i} \sim m_{l_i}^2$ ($i=1,2,3$). Parameters and corresponding masses for leptonic sector with predicted mass values of the fourth family leptons are presented in Table 2, where m_{ν_1} is taken to be 1 eV.

Leptonic CKM matrix is $O_{CKM} = O_\nu O_l^T$, where O_ν and O_l are rotations which diagonalize neutrino and charged lepton mass matrices respectively. For the case of (i), we obtain a matrix

$$O_{CKM}^l = \begin{pmatrix} 0.9999 & 0.0000 & 0.0001 & 0.0000 \\ 0.0000 & 0.9999 & -0.0023 & 0.0003 \\ -0.0002 & 0.0023 & 0.9999 & -0.0040 \\ 0.0000 & -0.0003 & 0.0040 & 0.9999 \end{pmatrix} \quad (5)$$

which is close to identity matrix, as expected. For (ii), we have

$$O_{CKM}^l = \begin{pmatrix} 0.9979 & 0.0645 & 0.0001 & 0.0000 \\ -0.0637 & 0.9848 & -0.1615 & 0.0010 \\ -0.0105 & 0.1612 & 0.9869 & -0.0039 \\ 0.0000 & -0.0003 & 0.0040 & 0.9999 \end{pmatrix} \quad (6)$$

Actually leptonic CKM mixings are not so sensitive to absolute value of m_{ν_1} . For example, taking m_{ν_1} to be 10^{-3} eV leads to practically the same matrices (5) and (6) for cases (i) and (ii), respectively. Case (ii) predicts too large values for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations, which are excluded by experimental data unless extremely small values of differences between squared masses of corresponding neutrino states have been realized [8].

Taking into account the predicted fourth family fermion masses, given in Tables 1 and 2, together with quark and lepton CKM matrices, one sees that dominant decay modes of these fermions are following:

$$u_4 \rightarrow b + W^+, \nu_4 \rightarrow \tau^- + W^+, d_4 \rightarrow u_4 + W^-, l_4 \rightarrow \nu_\tau + W^-.$$

The mass spectrum allows, in principal, additional decay modes of ν_4 : $l_4 + \bar{c} + \nu_e$, $l_4 + \bar{\mu} + \nu_\mu$, $l_4 + \bar{\tau} + \nu_\tau$, $l_4 + u + \bar{d}$, $l_4 + c + \bar{s}$. Let us compare these decay modes with $\nu_4 \rightarrow \tau^- + W^+$. Simple calculations yield

$$\Gamma(\nu_4 \rightarrow \tau + W) = \frac{G_F m_{\nu_4}^3}{8\sqrt{2}\pi} (1-y)^2 (1+2y) |O_{\nu_4\tau}|^2$$

where $y = m_W/m_{l_i}$ and $O_{\nu_4\tau}$ denotes corresponding element of leptonic CKM matrix. With our parameters, we obtain $\Gamma(\nu_4 \rightarrow \tau + W) \sim 1$ Mev. For three fermion decay modes, neglecting the masses of ligh fermions, one has

$$\Gamma(\nu_4 \rightarrow l_4 + f_1 + f_2) = n_c \frac{G_F^2}{30\pi^3} (m_{\nu_4} - m_{l_4})^5$$

here, $n_c = 1$ for leptons and $n_c = 3$ for quarks. Therefore the total width of these decay modes is about 0.2 eV which is negligible comparing with $\Gamma(\nu_4 \rightarrow \tau + W)$.

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TABLE I. Parameters and corresponding mass values for quark sector.

	$\gamma = -0.00034$	$\beta = -0.012$	$\alpha = -0.5$	
up quarks	$m_u = 6.9 \text{ MeV}$	$m_c = 1.28 \text{ GeV}$	$m_t = 189 \text{ GeV}$	$m_{u_4} = 504 \text{ GeV}$
	$\gamma = -0.00015$	$\beta = -0.0012$	$\alpha = -0.017$	
down quarks	$m_d = 12.6 \text{ MeV}$	$m_s = 136 \text{ MeV}$	$m_b = 4.3 \text{ GeV}$	$m_{d_4} = 633 \text{ GeV}$

TABLE II. Parameters and corresponding mass values for lepton sector.

	$\gamma = -5257 \times 10^{-14}$	$\beta = -2716 \times 10^{-12}$	$\alpha = -1305 \times 10^{-11}$	
$m_{\nu_i} \sim m_{l_i}$	$m_{\nu_1} = 1 \text{ eV}$	$m_{\nu_2} = 206.7 \text{ eV}$	$m_{\nu_3} = 3477 \text{ eV}$	$m_{\nu_4} = 640 \text{ GeV}$
	$\gamma = -7462 \times 10^{-13}$	$\beta = -4046 \times 10^{-10}$	$\alpha = -5023 \times 10^{-8}$	
$m_{\nu_i} \sim m_{l_i}^2$	$m_{\nu_1} = 1 \text{ eV}$	$m_{\nu_2} = 42.75 \text{ keV}$	$m_{\nu_3} = 12.09 \text{ MeV}$	$m_{\nu_4} = 640 \text{ GeV}$
	$\gamma = -0.00002687$	$\beta = -0.001394$	$\alpha = -0.006619$	
charged leptons	$m_e = 0.511 \text{ MeV}$	$m_\mu = 105.65 \text{ MeV}$	$m_\tau = 1.7771 \text{ GeV}$	$m_{l_4} = 637 \text{ GeV}$