CP Violation, Fermion Masses and Mixings in a Predictive SUSY

$SO(10) \times \Delta(48) \times U(1)$ Model with Small $\tan \beta$

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Abstract

Fermion masses and mixing angles are studied in an SUSY $SO(10) \times \Delta(48) \times U(1)$ model with small $\tan \beta$. Thirteen parameters involving masses and mixing angles in the quark and charged lepton sector are successfully predicted by a single Yukawa coupling and three ratios of VEVs caused by necessary symmetry breaking. Ten relations among the low energy parameters have been found with four of them free from renormalization modifications. They could be tested directly by low energy experiments.

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The standard model (SM) is a great success. Eighteen phenomenological parameters in the SM, which are introduced to describe all the low energy data, have been extracted from various experiments although they are not yet equally well known. Some of them have an accuracy of better than 1%, but some others less than 10%. To improve the accuracy for these parameters and understand them is a big challenge for particle physics. The mass spectrum and the mixing angles observed remind us that we are in a stage similar to that of atomic spectroscopy before Balmer. Much effort has been made along this direction. The well-known examples are the Fritzsch ansatz [1] and Georgi-Jarlskog texture [2]. A general analysis and review of the previous studies on the texture structure was given by Raby in [3]. Recently, Babu, and Barr [4], and Mohapatra [5], and Shafi [6], Hall and Raby [7], Berezhiani [8], Kaplan and Schmaltz [9], Kusenko and Shrock [10] constructed some interesting models with texture zeros based on supersymmetric (SUSY) SO(10). Anderson, Dimopoulos, Hall, Raby, and Starkman [11] presented a general operator analysis for the quark and charged lepton Yukawa coupling matrices with two zero textures ‘11’ and ‘13’. The 13 observables in the quark and charged lepton sector were found to be successfully fitted by only six parameters with large tanβ. Along this direction, we have shown [12] that the same 13 parameters can be successfully described, in an SUSY SO(10) × Δ(48) × U(1) model with large values of tanβ ~ mt/mb, by only five parameters with three of them determined by the symmetry breaking scales of U(1), SO(10), SU(5), and SU(2)L. Ten parameters in the neutrino sector could also be predicted, though not unique, with one additional parameter.

In this Rapid Communication, we shall present, based on the symmetry group SUSY SO(10) × Δ(48) × U(1), an alternative model with small values of tanβ ~ 1 which is of phenomenological interest in testing the Higgs sector in the minimum supersymmetric standard model (MSSM) at Colliders [13]. The dihedral group Δ(48), a subgroup of SU(3), is taken as the family group. U(1) is family-independent and is introduced to distinguish various fields which belong to the same representations of SO(10) × Δ(48). The irreducible representations of Δ(48) consisting of five triplets and three singlets are found to be sufficient to build an interesting texture structure for fermion mass matrices. The symmetry
$\Delta(48) \times U(1)$ naturally ensures the texture structure with zeros for Yukawa coupling matrices, while the coupling coefficients of the resulting interaction terms in the superpotential are unconstrained by this symmetry. To reduce the possible free parameters, the universality of coupling constants in the superpotential is assumed, i.e., all the coupling coefficients are assumed to be equal and have the same origins from perhaps a more fundamental theory. We know in general that universality of charges occurs only in the gauge interactions due to charge conservation like the electric charge of different particles. In the absence of strong interactions family symmetry could keep the universality of weak interaction in a good approximation after breaking. In our case there are so many heavy fermions above the grand unification theory (GUT) scale and their interactions are taken to be universal in the GUT scale where family symmetries have been broken. It can only be an ansatz at the present moment where we do not know the answer governing the behavior of nature above the GUT scale. As the numerical predictions on the low energy parameters so found are very encouraging and interesting, we believe that there must be a deeper reason that has to be found in the future.

Choosing the structure of the physical vacuum carefully, the Yukawa coupling matrices which determine the masses and mixings of all quarks and leptons are given by

$$
\Gamma^G_u = \frac{2}{3} \lambda_H \left( \begin{array}{ccc}
0 & \frac{3}{2} z_u' \epsilon_P^2 & 0 \\
\frac{3}{2} z_u \epsilon_P^2 & -3 y_u \epsilon^2 e^{i\phi} & -\frac{\sqrt{3}}{2} x_u \epsilon_G^2 \\
0 & -\frac{\sqrt{3}}{2} x_u \epsilon_G^2 & w_u
\end{array} \right) \quad (1)
$$

and

$$
\Gamma^G_f = \frac{2}{3} \lambda_H \frac{1}{3^n} \left( \begin{array}{ccc}
0 & -\frac{3}{2} z_f' \epsilon_P^2 & 0 \\
\frac{3}{2} z_f \epsilon_P^2 & 3 y_f \epsilon_G^2 e^{i\phi} & -\frac{1}{2} x_f \epsilon_G^2 \\
0 & -\frac{1}{2} x_f \epsilon_G^2 & w_f
\end{array} \right) \quad (2)
$$

for $f = d, e$, and

$$
\Gamma^G_\nu = \frac{2}{3} \lambda_H \frac{1}{5} \frac{(-1)^{n+1}}{15^n} \left( \begin{array}{ccc}
0 & -\frac{15}{2} z' \epsilon_P^2 & 0 \\
\frac{15}{2} z \epsilon_P^2 & 15 y \epsilon_G^2 e^{i\phi} & -\frac{1}{2} x \epsilon_G^2 \\
0 & -\frac{1}{2} x \epsilon_G^2 & w\nu
\end{array} \right) \quad (3)
$$
for Dirac-type neutrino coupling, where the integer \( n \) reflects the possible choice of heavy fermion fields above the GUT scale. \( n = 4 \) is found to be the best choice in this set of models for a consistent prediction on top and charm quark masses. This is because for \( n > 4 \), the resulting value of \( \tan \beta \) becomes too small, as a consequence, the predicted top quark mass will be below the present experimental lower limit. For \( n < 4 \), the values of \( \tan \beta \) will become larger, the resulting charm quark mass will be above the present upper bound. \( \lambda_H \) is an universal coupling constant expected to be of order one. \( \epsilon_G \equiv v_5/v_{10} \) and \( \epsilon_P \equiv v_5/\bar{M}_P \) with \( \bar{M}_P, v_{10}, \) and \( v_5 \) being the vacuum expectation values (VEVs) for \( U(1) \times \Delta(48), SO(10) \) and \( SU(5) \) symmetry breaking respectively. \( \phi \) is the physical CP phase arising from the VEVs. The assumption of maximum CP violation implies that \( \phi = \pi/2. \) \( x_f, y_f, z_f, \) and \( w_f \) \( (f = u, d, e, \nu) \) are the Clebsch factors of \( SO(10) \) determined by the directions of symmetry breaking of the adjoints 45’s. The three directions of symmetry breaking have been chosen as \( < A_X > = v_{10} \) diag.\( (2, 2, 2, 2, 2) \otimes \tau_2, < A_z > = v_5 \) diag.\( ( -\frac{2}{3}, -\frac{2}{3}, -\frac{2}{3}, -2, -2) \otimes \tau_2, \) \( < A_u > = v_5 \) diag.\( (\frac{2}{3}, \frac{2}{3}, \frac{2}{3}, 1, \frac{1}{3}) \) \( \otimes \tau_2. \) The Clebsch factors associated with the symmetry breaking directions can be easily read off from the \( U(1) \) hypercharges of the adjoints 45’s and the related effective operators which are obtained when the symmetry \( SO(10) \times \Delta(48) \times U(1) \) is broken and heavy fermion pairs are integrated out and decoupled:

\[
W_{33} = (\frac{2}{3} \lambda_H) \frac{3}{2} \epsilon_G \frac{\sqrt{3}}{2} 16_3 \frac{\sqrt{3}}{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} (\frac{v_{10}}{A_X})^{n+1} 10_1 (\frac{v_{10}}{A_X})^{n+1} \frac{\sqrt{3}}{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} 16_3
\]

\[
W_{32} = (\frac{2}{3} \lambda_H) \frac{3}{2} \epsilon_G \frac{\sqrt{3}}{2} 16_3 \frac{\sqrt{3}}{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} (\frac{v_{10}}{A_X})^{n+1} (\frac{A_z}{v_5}) (\frac{v_{10}}{A_X}) 10_1 (\frac{v_{10}}{A_X}) (\frac{A_z}{v_5}) (\frac{v_{10}}{A_X})^{n+1} 16_2
\]

\[
W_{22} = (\frac{2}{3} \lambda_H) \frac{3}{2} \epsilon_G \frac{3}{2} 16_2 \frac{\sqrt{3}}{2} \frac{\sqrt{3}}{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} (\frac{v_{10}}{A_X})^{n+1} (\frac{A_u}{v_5}) A_X (\frac{v_{10}}{A_X}) 10_1 (\frac{v_{10}}{A_X}) (\frac{A_u}{v_5}) (\frac{v_{10}}{A_X})^{n+1} 16_2 \epsilon^\phi
\]

\[
W_{12} = (\frac{2}{3} \lambda_H) \frac{3}{2} \epsilon_G \frac{3}{2} 16_1 \frac{\sqrt{3}}{2} \frac{\sqrt{3}}{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} (\frac{v_{10}}{A_X})^{n+1} (\frac{A_u}{v_5}) (\frac{v_{10}}{A_X}) (\frac{v_{10}}{A_X})^{n+1} 16_1
\]

The factor \( 1/\sqrt{1 + 2(\frac{v_5}{A_X})^{2(n+1)}} \) arising from the mixing, is equal to \( 1/\sqrt{3} \) for the up-type quark and almost unity for other fermions due to suppression of large Clebsch factors in the second term of the square root. The relative phase (or sign) between the two terms in the
operator $W_{12}$ has been fixed. The resulting Clebsch factors are $w_u = w_d = w_e = w_\nu = 1,$ $x_u = 5/9, x_d = 7/27, x_e = -1/3, x_\nu = 1/5 y_u = 0, y_d = y_e/3 = 2/27, y_\nu = 4/45,$ $z_u = 1, z_d = z_e = -27, z_\nu = -15^3 = -3375, z'_u = 1 - 5/9 = 4/9, z'_d = z'_e = 7/729 \simeq z_d,$ $z'_e = z_e - 1/81 \simeq z_e, z'_e = z_\nu + 1/15^3 \simeq z_\nu.$

An adjoint $45$ $A_X$ and a 16-dimensional representation Higgs field $\Phi$ ($\bar{\Phi}$) are needed for breaking SO(10) down to SU(5). Another two adjoint 45s $A_z$ and $A_u$ are needed to break SU(5) further down to the standard model $SU(3)_C \times SU_L(2) \times U(1)_Y$. From the Yukawa coupling matrices given above, the 13 parameters in the SM can be determined by only four parameters: a universal coupling constant $\lambda_H$ and three ratios of the VEVs: $\epsilon_G = v_5/v_{10}, \epsilon_\rho = v_5/M_P$ and $\tan \beta = v_2/v_1$. In obtaining physical masses and mixings, renormalization group (RG) effects should be taken into account. As most Yukawa couplings in the present model are much smaller than the top quark Yukawa coupling $\lambda_t \sim 1$, in a good approximation, we will only keep top quark Yukawa coupling terms in the RG equations and neglect all other Yukawa coupling terms. The RG evolution will be described by three kinds of scaling factors. $\eta_F (F = U, D, E, N)$ and $R_t$ arise from running the Yukawa parameters from the GUT scale down to the SUSY breaking scale $M_S$ which is chosen to be close to the top quark mass, i.e., $M_S \simeq m_t \simeq 170$ GeV. They are defined by $\eta_F(M_S) = \Pi_{i=1}^3 \left( \frac{a_i(M_G)}{a_i(M_S)} \right)^{c_i^{F}/2b_i} (F = U, D, E, N)$ with $c_i^U = (\frac{13}{10}, 3, \frac{16}{3})$, $c_i^D = (\frac{7}{10}, 3, \frac{16}{3})$, $c_i^E = (\frac{7}{10}, 3, 0)$, $c_i^N = (\frac{9}{25}, 3, 0)$, $b_i = (\frac{23}{5}, 1, -3)$, and $R_t^{-1} = \exp[- \int_{\ln M_S}^{\ln M_G} (\lambda_t(t) \lambda_t(t))^{2} dt] = [1 + (\lambda_t^G)^2 K_t]^{-1/12}$, where $K_t = \frac{3f(M_S)}{4\pi^2}$ with $I(M_S) = \int_{\ln M_S}^{\ln M_G} \eta_U^2(t) dt$. The numerical value for $I$ taken from Ref. [5] is 113.8 for $M_S \simeq m_t = 170$ GeV. Other RG scaling factors are derived by running Yukawa couplings below $M_S$. $m_i(m_i) = \eta_i m_i(M_S)$ for $(i = c, b)$ and $m_i(1 \text{GeV}) = \eta_i m_i(M_S)$ for $(i = u, d, s)$. The physical top quark mass is given by $M_t = m_t(m_t) \left( 1 + \frac{4\alpha(m_t)}{3} \right)$. Using the well-measured charged lepton masses $m_e = 0.511$ MeV, $m_\mu = 105.66$ MeV, and $m_\tau = 1.777$ GeV, we obtain four important RG scaling-independent predictions:

$$|V_{us}| = |V_{us}|_G \simeq 3 \sqrt{\frac{m_e}{m_\mu}} \left( \frac{1 + (\frac{16 m_e}{675 m_\mu})^2}{1 + 9 \frac{m_e}{m_\mu}} \right)^{1/2} = 0.22,$$  

(5)
\[ \frac{|V_{ub}|}{|V_{cb}|} = |V_{ub}|_{G} \approx (\frac{4}{15})^{2} \frac{m_{\tau}}{m_{\mu}} \sqrt{\frac{m_{e}}{m_{\mu}}} = 0.083, \]  
(6)

\[ \frac{|V_{td}|}{|V_{ts}|} = |V_{td}|_{G} \approx 3 \sqrt{\frac{m_{e}}{m_{\mu}}} = 0.209, \]  
(7)

\[ \frac{m_{d}}{m_{s}} (1 - \frac{m_{d}}{m_{s}})^{-2} = 9 \frac{m_{e}}{m_{\mu}} (1 - \frac{m_{e}}{m_{\mu}})^{-2} = 0.044 \]  
(8)

and six RG scaling-dependent predictions

\[ |V_{cb}| = |V_{cb}|_{G} R_{t} \approx \frac{15 \sqrt{3} - 7}{15 \sqrt{3}} \frac{5}{4 \sqrt{3} m_{\tau}} m_{\mu} R_{t} = 0.0391 \left( \frac{0.80}{R_{t}^{-1}} \right), \]  
(9)

\[ m_{s}(1 GeV) = \frac{1}{3} m_{\mu} \frac{\eta_{u}}{\eta_{\mu}} \eta_{D/E} = 159.53 \left( \frac{\eta_{s}}{2.2} \right) \left( \frac{\eta_{D/E}}{2.1} \right) \text{ MeV}, \]  
(10)

\[ m_{b}(m_{b}) = m_{\tau} \frac{\eta_{u}}{\eta_{\tau}} \eta_{D/E} R_{t}^{-1} = 4.25 \left( \frac{\eta_{b}}{1.49} \right) \left( \frac{\eta_{D/E}}{2.04} \right) \left( \frac{R_{t}^{-1}}{0.80} \right) \text{ GeV}, \]  
(11)

\[ m_{u}(1 GeV) = \frac{5}{3} \left( \frac{4}{45} \right)^{3} \frac{m_{e}}{m_{\mu}} \eta_{u} R_{t}^{3} m_{t} = 4.23 \left( \frac{\eta_{u}}{2.2} \right) \left( \frac{0.80}{R_{t}^{-1}} \right)^{3} \left( \frac{m_{t}}{174 GeV} \right) \text{ MeV}, \]  
(12)

\[ m_{c}(m_{c}) = \frac{25}{48} \left( \frac{m_{\mu}}{m_{\tau}} \right)^{2} \eta_{c} R_{t}^{3} m_{t} = 1.25 \left( \frac{\eta_{c}}{2.0} \right) \left( \frac{0.80}{R_{t}^{-1}} \right)^{3} \left( \frac{m_{t}}{174 GeV} \right) \text{ GeV}, \]  
(13)

\[ m_{t}(m_{t}) = \frac{\eta_{t}}{\sqrt{K_{t}}} \sqrt{1 - R_{t}^{-12}} \frac{v}{\sqrt{2}} \sin \beta = 174.9 \left( \frac{\sin \beta}{0.92} \right) \left( \frac{\eta_{t}}{3.33} \right) \left( \frac{8.65}{K_{t}} \right) \left( \frac{\sqrt{1 - R_{t}^{-12}}}{0.965} \right) \text{ GeV} \]  
(14)

where the miraculus numbers in the above relations are due to the Clebsch factors. The scaling factor \( R_{t} \) or coupling \( \lambda_{\tau}^{2} = \frac{1}{\sqrt{K_{t}}} \sqrt{\frac{1 - R_{t}^{-12}}{R_{t}^{-6}}} \) is determined by the mass ratio of the bottom quark and \( \tau \) lepton. \( \tan \beta \) is fixed by the \( \tau \) lepton mass via \( \cos \beta = \frac{m_{\tau}}{\eta_{\mu} \eta_{\tau} \tau \beta}. \)

The above 10 relations are our main results which contain only low energy observables. As an analogy to the Balmer series formula, these relations may be considered as empirical at the present moment. They have been tested by the existing experimental data to a good approximation and can be tested further directly by more precise experiments in the future.

In numerical predictions we take \( \alpha^{-1}(M_{Z}) = 127.9, \ s^{2}(M_{Z}) = 0.2319, \ M_{Z} = 91.187 \) \( \text{GeV}, \ \alpha_{1}^{-1}(m_{t}) = 58.59, \ \alpha_{2}^{-1}(m_{t}) = 30.02 \) and \( \alpha_{3}^{-1}(M_{G}) = \alpha_{2}^{-1}(M_{G}) = \alpha_{3}^{-1}(M_{G}) \approx 24 \) with \( M_{G} \approx 2 \times 10^{16} \) \( \text{GeV}. \) For \( \alpha_{s}(M_{Z}) = 0.113, \) the RG scaling factors have values \( (\eta_{u,d,s}, \ \eta_{c}, \ \eta_{b}, \ \eta_{e,\mu,\tau}, \ \eta_{D/E} \equiv \eta_{D/E}, \ \eta_{E}, \ \eta_{N}) = (2.20, 2.00, 1.49, 1.02, 3.33, 2.06, 1.58, 1.41). \) The corresponding predictions on fermion masses and mixings thus obtained are found to be remarkable. Our numerical predictions for \( \alpha_{s}(M_{Z}) = 0.113 \) are given in table 1 with four
input parameters: three charged lepton masses and bottom quark mass $m_b(m_b) = 4.25$GeV, where $B_K$ and $f_B\sqrt{B}$ in table 1 are two important hadronic parameters and extracted from $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing parameters $\varepsilon_K$ and $x_d$. $Re(\varepsilon'/\varepsilon)$ is the direct CP-violating parameter in kaon decays, where large uncertainties mainly arise from the hadronic matrix elements. $\alpha$, $\beta$ and $\gamma$ are three angles of the unitarity triangle in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. $J_{CP}$ is the rephase-invariant CP-violating quantity.

It is amazing that nature has allowed us to make predictions on fermion masses and mixings in terms of a single Yukawa coupling constant and three ratios of the VEVs determined by the structure of the physical vacuum and understand the low energy physics from the GUT scale physics. It has also suggested that nature favors maximal spontaneous CP violation. A detailed analysis including the neutrino sector will be presented in a longer paper [20]. In comparison with the models with large $\tan \beta \sim m_t/m_b$, the present model has provided a consistent picture on the 13 parameters in the SM with better accuracy. Besides, ten relations involving fermion masses and CKM matrix elements are obtained with four of them independent of the RG scaling effects. The two types of the models corresponding to the large and low $\tan \beta$ might be distinguished by testing the MSSM Higgs sector at Colliders as well as by precisely measuring the ratio $|V_{ub}/V_{cb}|$ since this ratio does not receive radiative corrections in both models. It is expected that more precise measurements from CP violation and various low energy experiments in the near future could provide crucial tests on the ten relations obtained in the present model.

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Table 1. Output parameters and their predicted values with $\alpha_s(M_Z) = 0.113$ and input parameters: $m_e = 0.511$ eV, $m_\mu = 105.66$ MeV, $m_\tau = 1.777$ GeV, and $m_b = 4.25$ GeV.

| Output parameters | Output values | Data [14] | Output para. | Output values |
|-------------------|--------------|-----------|--------------|--------------|
| $M_t$ [GeV]       | 182          | 180 ± 15  | $J_{CP} = A^2 \lambda^6 \eta$ | $2.68 \times 10^{-5}$ |
| $m_c(m_c)$ [GeV]  | 1.27         | 1.27 ± 0.05 | $\alpha$ | 86.28° |
| $m_\mu(1\text{GeV})$ [MeV] | 4.31 | 4.75 ± 1.65 | $\beta$ | 22.11° |
| $m_\tau(1\text{GeV})$ [MeV] | 156.5 | 165 ± 65 | $\gamma$ | 71.61° |
| $m_b(1\text{GeV})$ [MeV] | 6.26 | 8.5 ± 3.0 | $\tan \beta = v_2/v_1$ | 2.33 |
| $|V_{us}| = \lambda$ | 0.22 | 0.221 ± 0.003 | $\epsilon_G = v_5/v_{10}$ | $2.987 \times 10^{-1}$ |
| $|V_{cb}| = \lambda \sqrt{\rho^2 + \eta^2}$ | 0.083 | 0.08 ± 0.03 | $\epsilon_P = v_5/\bar{M}_P$ | $1.011 \times 10^{-2}$ |
| $|V_{td}| = \lambda \sqrt{(1 - \rho)^2 + \eta^2}$ | 0.209 | 0.24 ± 0.11 | $\lambda^G$ | 1.30 |
| $|V_{ub}| = A \lambda^2$ | 0.0393 | 0.039 ± 0.005 [19] | - | - |
| $B_K$             | 0.90         | 0.82 ± 0.10 [17,18] | - | - |
| $f_B\sqrt{B}$ [MeV] | 207 | 200 ± 70 [18,16] | - | - |
| $Re(\varepsilon'/\varepsilon)$ | (1.4 ± 1.0) • $10^{-3}$ | (1.5 ± 0.8) • $10^{-3}$ | - | - |
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