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Flipped $SO(10)$ model

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Abstract

This Letter demonstrates that, as in flipped $SU(5)$ models, doublet-triplet splitting is accomplished by a missing partner mechanism in flipped $SO(10)$ models. The gauge group $SO(10)_F \times U(1)_{V'_F}$ includes $SU(2)_E$ gauge symmetry, which plays an important role in solving the supersymmetric (SUSY) flavor problem by introducing non-abelian horizontal gauge symmetry and anomalous $U(1)_A$ gauge symmetry. The gauge group can be broken into the standard model gauge group by VEVs of only spinor fields; such models may be easier to derive than E_6 models from superstring theory.

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1. Introduction

In a previous paper [1], one of the authors indicated that the SUSY flavor problem can be solved in E_6 unification by using non-abelian horizontal gauge symmetry and anomalous $U(1)_A$ gauge symmetry [2], with anomaly cancelled by the Green–Schwarz mechanism [3], even if large neutrino mixing angles are obtained. An essential aspect is that the fundamental representation **27** of E_6 has two $\bar{\mathbf{5}}$ fields of $SU(5)$. Actually **27** is decomposed as

$$\mathbf{27} \to \underbrace{[\mathbf{10}_{(1,1)} + \bar{\mathbf{5}}_{(1,-3)} + \mathbf{1}_{(1,5)}]}_{\mathbf{16}_1} + \underbrace{[\bar{\mathbf{5}}_{(-2,2)} + \mathbf{5}_{(-2,-2)}]}_{\mathbf{10}_{-2}} + \underbrace{[\mathbf{1}_{(4,0)}]}_{\mathbf{1}_4} \tag{1.1}$$

under $E_6 \supset SO(10) \times U(1)_{V'} \supset SU(5) \times U(1)_{V'} \times U(1)_V$, where the representations of $SO(10) \times U(1)_{V'}$ and $SU(5) \times U(1)_{V'} \times U(1)_V$ are explicitly denoted in the above. If three **27** fields Ψ_i $(i = 1, 2, 3)$ for three generation quarks and leptons are introduced, three of six $\bar{\mathbf{5}}$ fields become massive with three **5** fields after dividing E_6 into $SU(5)$, and the remaining fields $(3 \times \bar{\mathbf{5}})$ remain massless. In the 6×3 mass matrix for $\bar{\mathbf{5}}$ and **5** fields, one naturally expects that the elements for the third generation field Ψ_3 become larger to produce larger Yukawa couplings than the first and second generation fields Ψ_1 and Ψ_2. Therefore, all the three massless modes of $\bar{\mathbf{5}}$ come mainly from the first two generation fields Ψ_1 and Ψ_2. This structure is interesting because it can explain larger mixing angles of the lepton sector than of the quark sector as discussed in Ref. [4]. Moreover, if non-abelian horizontal symmetry

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$SU(2)_H$ is introduced and the first two generation fields are taken as doublets, then all three generation $\bar{\mathbf{5}}$ fields have degenerate sfermion masses, which are very important in suppressing flavor changing neutral current (FCNC) processes with large neutrino mixing angles as discussed in Ref. [1].

The E_6 gauge group plays an important role in these postulates. Actually, an essential point is that a single field includes two $\bar{\mathbf{5}}$ fields to achieve large neutrino mixing angles with suppressing FCNC processes. In order to break down E_6 to the standard model (SM) gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, adjoint Higgs fields **78** are required, which may not be easily accomplished in the framework of superstring models. A simple way of avoiding adjoint Higgs is to adopt a non-simple group as a unification group. Which kinds of non-simple groups do not spoil the interesting features mentioned? The answer is simple. In order to satisfy the essential point that two fields with the same quantum number under the SM gauge group are included in a single multiplet, $SU(2)_E$, which is a subgroup of E_6 group and rotates $(\bar{\mathbf{5}}_{(1,-3)}, \bar{\mathbf{5}}_{(-2,2)})$ and $(\mathbf{1}_{(1,5)}, \mathbf{1}_{(4,0)})$ as doublets, is sufficient. Therefore, an interesting point to consider is the unification group that includes $SU(2)_E$. The $SU(3)^3 \subset E_6$ is an example and a realistic $SU(3)^3$ model can be straightforwardly constructed [5], in which the doublet-triplet splitting problem is solved and realistic quark and lepton mass matrices are obtained including large neutrino mixing angles. Therefore, if non-abelian horizontal symmetry is introduced in addition to $SU(3)^3$, FCNC processes can be naturally suppressed with large neutrino mixing angles. This Letter considers another non-simple gauge group, $SO(10)_F \times U(1)_{V'_F}$, which can include $SU(2)_E$ because of the unusual embedding of the SM gauge group. In this model, doublet-triplet splitting is accomplished by a missing partner mechanism. The original missing partner mechanism was introduced in the $SU(5)$ unification group [6], but it requires several large dimensional representation Higgs fields. To avoid the large dimensional Higgs fields, a flipped $SU(5)$ [7] has been considered. The gauge group $SU(5)_F \times U(1)_X$ cannot be unified into $SO(10)$ without spoiling the missing partner mechanism, but $SO(10)_F \times U(1)_{V'_F} \subset E_6$ can embed the flipped $SU(5)$ without spoiling the missing partner mechanism. As noted, the flipped $SO(10)$ gauge group includes $SU(2)_E$, which is important in solving the SUSY flavor problem by introducing non-abelian horizontal gauge symmetry and anomalous $U(1)_A$ gauge symmetry.

2. Review of flipped $SU(5)$ model

This section briefly reviews the flipped $SU(5)$ model and the reason why the flipped $SU(5)$ model cannot be embedded in $SO(10)$ GUT.

One family standard model fermions $Q(\mathbf{3},\mathbf{2})_{1/6}$, $U^c(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$, $D^c(\bar{\mathbf{3}},\mathbf{1})_{1/3}$, $L(\mathbf{1},\mathbf{2})_{-1/2}$, and $E^c(\mathbf{1},\mathbf{1})_1$ plus the right-handed neutrino $N^c(\mathbf{1},\mathbf{1})_0$ under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ are unified into an $SO(10)$-spinorial **16** superfield:

$$\Psi(\mathbf{16}) \to \mathbf{10}_\Psi(\mathbf{10}_1) + \bar{\mathbf{5}}_\Psi(\bar{\mathbf{5}}_{-3}) + \mathbf{1}_\Psi(\mathbf{1}_5), \tag{2.1}$$

where the decomposition is specified into $SU(5) \times U(1)_V$. The matter content of the flipped $SU(5)$ models can be obtained from the corresponding assignment of the standard $SU(5)$ GUT model by means of "flipping" $U^c \leftrightarrow D^c$ and $N^c \leftrightarrow E^c$:

$$\mathbf{10}_\Psi = \left(Q, D^c, N^c\right), \qquad \bar{\mathbf{5}}_\Psi = \left(U^c, L\right), \qquad \mathbf{1}_\Psi = E^c. \tag{2.2}$$

An important point is that if $\mathbf{10}_1$ representation Higgs $\mathbf{10}_C$ is introduced, $SU(5) \times U(1)_X$ can be broken down to the standard model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ by the vacuum expectation value (VEV) of the component of N^c. Here, the hypercharge operator is written

$$Y = \frac{1}{5}(X - Y'), \tag{2.3}$$

where Y' is the generator of $SU(5)_F$ which commutes with $SU(3)_C \times SU(2)_L$. Then the $SO(10)$-vectorial **10** superfield decomposed as

$$H(\mathbf{10}) \to \mathbf{5}_H(\mathbf{5}_{-2}) + \bar{\mathbf{5}}_H(\bar{\mathbf{5}}_2) \tag{2.4}$$

includes the SM doublet Higgs $H_d = L'$ and $H_u = \bar{L}'$ as

$$\mathbf{5}_H = \left(\overline{D}^{c\prime}, L'\right), \qquad \bar{\mathbf{5}}_H = \left(D^{c\prime}, \bar{L}'\right), \tag{2.5}$$

where $D^{c\prime}$ and L' have the same quantum number of the SM gauge group as D^c and L, respectively. If interactions are introduced in the superpotential as

$$W_{\mathrm{MP}} = \mathbf{10}_C\mathbf{10}_C\mathbf{5}_H + \overline{\mathbf{10}}_{\overline{C}}\overline{\mathbf{10}}_{\overline{C}}\bar{\mathbf{5}}_H, \tag{2.6}$$

only the triplet Higgs $\overline{D}^{c\prime}$ and $D^{c\prime}$ can be superheavy with D^c in $\mathbf{10}_C$ and $\overline{D}^c$ in $\overline{\mathbf{10}}_{\overline{C}}$, respectively, by developing the VEVs of $\mathbf{10}_C$ and $\overline{\mathbf{10}}_{\overline{C}}$, but the doublet Higgs L' and $\bar{L}'$ have no partner and remain massless. This is essential for the missing partner mechanism in the flipped $SU(5)$ model.

Unfortunately, this missing partner mechanism in the flipped $SU(5)$ model cannot be extended to $SO(10)$ unification. In $SO(10)$ unification, the interactions (2.6) are included in the $SO(10)$ symmetric interactions $C(\mathbf{16})C(\mathbf{16})H(\mathbf{10})$ and $\overline{C}(\overline{\mathbf{16}})\overline{C}(\overline{\mathbf{16}})H(\mathbf{10})$, which also include

$$\mathbf{10}_C\bar{\mathbf{5}}_C\bar{\mathbf{5}}_H + \overline{\mathbf{10}}_{\overline{C}}\mathbf{5}_{\overline{C}}\mathbf{5}_H. \tag{2.7}$$

Through these interactions, the doublet Higgs $(\bar{L}')_H$ and $(L')_H$ become superheavy with L_C and $(L^*)_{\overline{C}}$, respectively, by developing the VEVs of $\mathbf{10}_{\overline{C}}$ and $\overline{\mathbf{10}}_{\overline{C}}$. (In this Letter, X^* is a component of $\overline{\mathbf{16}}$ of $SO(10)$ and denotes the complex conjugate representation of X, which is a component of **16** of $SO(10)$.) Therefore, doublet-triplet splitting is spoiled by this extension.[1]

The next section shows that the missing partner mechanism for the flipped $SU(5)$ model can be embedded in the $SO(10)_F \times U(1)_{V_F'}$ unification group.

3. Flipped *SO*(10) model

As noted in the introduction, **27** of E_6 is decomposed as

$$\mathbf{27} \to \underbrace{[\mathbf{10}_{(1,1)} + \bar{\mathbf{5}}_{(1,-3)} + \mathbf{1}_{(1,5)}]}_{\mathbf{16}_1} + \underbrace{[\bar{\mathbf{5}}_{(-2,2)} + \mathbf{5}_{(-2,-2)}]}_{\mathbf{10}_{-2}} + \underbrace{[\mathbf{1}_{(4,0)}]}_{\mathbf{1}_4} \tag{3.1}$$

under $E_6 \supset SO(10) \times U(1)_{V'} \supset SU(5) \times U(1)_{V'} \times U(1)_V$. There are two ways to embed the flipped $SU(5)$ matters $\mathbf{10}_\Psi = (Q, D^c, N^c)$, $\bar{\mathbf{5}}_\Psi = (U^c, L)$ and $\mathbf{1}_\Psi = E^c$ in the above decomposition of **27** of E_6 into $SO(10) \times U(1)_{V'}$. As discussed in the previous section, the usual embedding $SU(5)_F \times U(1)_X$ in $SO(10)$,

$$\underbrace{[\mathbf{10}_\Psi + \bar{\mathbf{5}}_\Psi + \mathbf{1}_\Psi]}_{\mathbf{16}_1} + \underbrace{[\bar{\mathbf{5}}_H + \mathbf{5}_H]}_{\mathbf{10}_{-2}} + \underbrace{[\mathbf{1}_S]}_{\mathbf{1}_4}, \tag{3.2}$$

where $\mathbf{5}_H = (\overline{D}^{c\prime}, L')$, $\bar{\mathbf{5}}_H = (D^{c\prime}, \bar{L}')$ and $\mathbf{1}_S$ is singlet under $SU(5)_F \times U(1)_X$, spoils the missing partner mechanism. The other embedding can be obtained by means of "flipping" $\bar{\mathbf{5}}_\Psi \leftrightarrow \bar{\mathbf{5}}_H$ and $\mathbf{1}_\Psi \leftrightarrow \mathbf{1}_S$:

$$\underbrace{[\mathbf{10}_\Psi + \bar{\mathbf{5}}_H + \mathbf{1}_S]}_{\mathbf{16}_1} + \underbrace{[\bar{\mathbf{5}}_\Psi + \mathbf{5}_H]}_{\mathbf{10}_{-2}} + \underbrace{[\mathbf{1}_\Psi]}_{\mathbf{1}_4}. \tag{3.3}$$

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[1] Of course, if we neglect the component fields $\bar{\mathbf{5}}_C$ and $\mathbf{5}_{\overline{C}}$ by hand, such extension becomes possible [8].

In this embedding, if $\mathbf{1}_S$ component of $\mathbf{16}_1$ field has non-vanishing VEV, $SO(10)_F \times U(1)_{V'_F}$ is broken down to $SU(5)_F \times U(1)_X$. Here, the operator X is obtained as

$$X = \frac{1}{4}\left(5V'_F - V_F\right), \tag{3.4}$$

where V_F is the generator of $SO(10)_F$ which commutes with $SU(5)_F$. The hypercharge operator is

$$Y = \frac{1}{5}(X - Y') = \frac{1}{20}\left(5V'_F - V_F - 4Y'\right). \tag{3.5}$$

Note that the each $SU(2)_E$ doublet $(D^{c\prime}, D^c)$, (L', L) and (N^c, S), a component of which has the same quantum number of SM gauge group as the other component, is included in a single multiplet $\mathbf{16}_1$, $\mathbf{10}_{-2}$ and $\mathbf{16}_1$, respectively. This means that $SU(2)_E$ is embedded in $SO(10)_F$.

Two pairs of Higgs fields $[\Phi(\mathbf{16}_1), \bar{\Phi}(\overline{\mathbf{16}}_{-1})]$ and $[C(\mathbf{16}_1), \bar{C}(\overline{\mathbf{16}}_{-1})]$ have been introduced to break down $SO(10)_F \times U(1)_{V'_F}$ to the SM gauge group. Supposing that the VEVs $|\langle\Phi\rangle| = |\langle\bar{\Phi}\rangle|$ break down $SO(10)_F \times U(1)_{V'_F}$ to $SU(5)_F \times U(1)_X$, the components $\mathbf{10}_\Phi$ and $\overline{\mathbf{10}}_{\bar{\Phi}}$ are absorbed by the Higgs mechanism. The VEVs $|\langle C\rangle| = |\langle\bar{C}\rangle|$ break down $SU(5)_F \times U(1)_X$ to the SM gauge group, and the components Q and N^c are absorbed by the Higgs mechanism. All of the remaining components $\bar{\mathbf{5}}_\Phi$, $\mathbf{5}_{\bar{\Phi}}$, $\bar{\mathbf{5}}_C$, $\mathbf{5}_{\bar{C}}$, $(D^c)_C$ and $(D^{c*})_{\bar{C}}$ must be massive except a pair of doublets. For example, through the interactions in the superpotential,

$$W_{SO(10)} = \bar{\Phi}\bar{\Phi}CC + \bar{C}\bar{C}\Phi\Phi, \tag{3.6}$$

which include the interactions (2.6) after developing the VEVs $|\langle\Phi\rangle| = |\langle\bar{\Phi}\rangle|$, pairs $[(D^{c\prime *})_{\bar{\Phi}}, (D^c)_C]$ and $[(D^{c\prime})_\Phi, (D^{c*})_{\bar{C}}]$ become massive. If a mass term is introduced for C and $\bar{C}$, then only $(\bar{L}')_\Phi$ and $(\bar{L}'^*)_{\bar{\Phi}}$ remain massless, namely, doublet-triplet splitting is realized. There are several interactions that unstabilize the doublet-triplet splitting. For example, the terms $\bar{\Phi}\Phi F(\bar{C}C, \bar{\Phi}\Phi)$ directly yield the doublet Higgs mass, so they must be forbidden. (This subject will be discussed later with a specific model.)

Three generation matter fields $\Psi_i(\mathbf{27}) = \mathbf{16}_{\Psi_i} + \mathbf{10}_{\Psi_i} + \mathbf{1}_{\Psi_i}$ $(i = 1, 2, 3)$ are assumed to respect E_6 symmetry. This is an easy way of guaranteeing the cancellation of gauge anomaly. Among the three generation matter fields Ψ_i, there are six fields that have the same quantum number under the SM gauge group as (D^c, L). Only three linear combinations of these fields become quarks and leptons, and other modes become superheavy with the three $(\bar{D}^{c\prime}, \bar{L}')$ fields through the interactions $\mathbf{16}_{\Psi_i}\mathbf{10}_{\Psi_j}\Phi$ and $\mathbf{16}_{\Psi_i}\mathbf{10}_{\Psi_j}C$ by developing the VEVs of Φ and C. An interesting point is that Yukawa couplings of the up quark sector can be obtained from the renormalizable interactions $\mathbf{16}_{\Psi_i}\mathbf{10}_{\Psi_j}\Phi$. Then, the $O(1)$ top Yukawa coupling can be naturally achieved. Yukawa couplings of the down quark sector and of the charged lepton sector are obtained from the higher-dimensional interactions $\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\bar{C}\bar{\Phi}$ and $\mathbf{10}_{\Psi_i}\mathbf{1}_{\Psi_j}\bar{C}\bar{\Phi}$, respectively. Because there are six singlets N_i^c and S_i in the matter sector, the mass matrix for right-handed neutrinos becomes a 6×6 matrix which is obtained from the interactions $\Psi_i\Psi_j\bar{\Phi}\bar{\Phi}$, $\Psi_i\Psi_j\bar{\Phi}\bar{C}$ and $\Psi_i\Psi_j\bar{C}\bar{C}$. Yukawa couplings of Dirac neutrino sector are obtained from the interactions $\mathbf{16}_{\Psi_i}\mathbf{10}_{\Psi_j}\Phi$. Therefore, the mass terms of all quarks and leptons can be obtained in this scenario.

Unfortunately, as in the flipped $SU(5)$ model, this missing partner mechanism in the flipped $SO(10)$ model cannot be extended to E_6 unification. In E_6 unification, the interactions (3.6) are included in the E_6 symmetric interactions $\Phi(\mathbf{27})\Phi(\mathbf{27})\bar{C}(\overline{\mathbf{27}})\bar{C}(\overline{\mathbf{27}})$ and $\bar{\Phi}(\overline{\mathbf{27}})\bar{\Phi}(\overline{\mathbf{27}})C(\mathbf{27})C(\mathbf{27})$, which also include $\mathbf{16}_\Phi\mathbf{10}_\Phi\mathbf{10}_{\bar{C}}\overline{\mathbf{16}}_{\bar{C}}$ and $\mathbf{16}_C\mathbf{10}_C\mathbf{10}_{\bar{\Phi}}\overline{\mathbf{16}}_{\bar{\Phi}}$ of $SO(10)_F$. After developing the VEVs $|\langle\Phi\rangle| = |\langle\bar{\Phi}\rangle|$, these interactions yield $\mathbf{5}_\Phi\mathbf{5}_{\bar{C}}\overline{\mathbf{10}}_{\bar{C}}$ and $\bar{\mathbf{5}}_{\bar{\Phi}}\bar{\mathbf{5}}_C\mathbf{10}_C$ of $SU(5)_F$, which give mass terms to doublet Higgs by taking non-vanishing VEVs $|\langle C\rangle| = |\langle\bar{C}\rangle|$. Therefore, doublet-triplet splitting is spoiled in this extension.

4. Flipped $SO(10)$ model with anomalous $U(1)_A$

An important point is to find a specific flipped $SO(10)$ model in which doublet-triplet splitting is achieved with generic interactions and to examine whether the realistic quark and lepton mass matrices are produced or not. In a series of papers [1,4,5,9–11], the authors have pointed out that anomalous $U(1)_A$ symmetry plays an important role in solving various problems in SUSY grand unified theory (GUT) with generic interactions. This is mainly because the SUSY zero mechanism (holomorphic zero)[2] can control various terms that must be forbidden.

This section presents a specific flipped $SO(10)$ model with generic interaction by introducing anomalous $U(1)_A$ symmetry.

4.1. Higgs sector

The Higgs contents are listed in Table 1. Following the general discussion on the determination of VEVs of the models with anomalous $U(1)_A$ charges, only the negatively charged fields can have non-vanishing VEVs [4,9–11]. The scales of these VEVs are determined by the anomalous $U(1)_A$ charges as

$$\langle\overline{\Phi}\Phi\rangle \sim \lambda^{-(\phi+\bar{\phi})}, \qquad \langle\overline{C}C\rangle \sim \lambda^{-(c+\bar{c})}, \tag{4.1}$$

where λ is the ratio of the VEV of Froggatt–Nielsen field Θ, which is essentially determined by the Fayet–Iliopoulos D-term parameter, to the cutoff Λ. In this Letter, λ is assumed to be around the Cabbibo angle $\sin\theta_C \sim 0.22$ and Λ is taken to be 1. If the $\mathbf{1}_{(1,5)}$ component of Φ and the $\mathbf{1}_{(-1,-5)}$ component of $\overline{\Phi}$ have non-vanishing VEVs, $SO(10)_F \times U(1)_{V'_F}$ is broken down to $SU(5)_F \times U(1)_X$. The $\mathbf{10}_{(1,1)}$ of Φ and $\overline{\mathbf{10}}_{(-1,-1)}$ of $\overline{\Phi}$ are absorbed by the Higgs mechanism at that time. Moreover, if the $\mathbf{10}_{(1,1)}$ component of C and the $\overline{\mathbf{10}}_{(-1,-1)}$ component of $\overline{C}$ have non-vanishing VEVs, $SU(5)_F \times U(1)_X$ is broken down to the SM gauge group. Then the Q component of $\mathbf{10}_{(1,1)}$ of C and the $\overline{Q}$ component of $\overline{\mathbf{10}}_{(-1,-1)}$ of $\overline{C}$ are absorbed by the Higgs mechanism. Therefore, the remaining negatively charged fields except singlets under the SM gauge group are the $\bar{\mathbf{5}}_{(1,-3)}$ components of Φ and C, the D^c component of C, and the mirror components of $\overline{\Phi}$ and $\overline{C}$. Among these negatively charged fields, no mass term appears because of the SUSY zero (holomorphic zero) mechanism. In order to make them massive, the positively charged fields Φ'_i and $\overline{\Phi}'_i$ must be taken into account. Note that in a $\mathbf{16}_1$ field, there are two colored Higgs D^c and $D^{c\prime}$ because of $SU(2)_E$ symmetry, but only one doublet $\bar{L}'$. Therefore, the colored

Table 1
The typical values of anomalous $U(1)_A$ charges are listed. $\pm$ is Z_2-parity and $i = 1, 2$

	Non-vanishing VEV	Vanishing VEV
$\mathbf{16}_1$	$\Phi(\phi = 0, -)$, $C(c = -2, +)$	$\Phi'_i(\phi'_i = 5, -)$
$\overline{\mathbf{16}}_{-1}$	$\overline{\Phi}(\bar{\phi} = -1, -)$, $\overline{C}(\bar{c} = -2, +)$	$\overline{\Phi}'_i(\bar{\phi}'_i = 4, -)$
$\mathbf{1}$	$\Theta(\theta = -1, +)$, $\overline{Z}_i(\bar{z}_i = -1, +)$, $Z(z = -4, -)$	$S'(s' = 8, +)$

[2] Note that if the total charge of an operator is negative, the $U(1)_A$ invariance and analytic property of the superpotential forbids the existence of the operator in the superpotential, since the Froggatt–Nielsen [12] field Θ with a negative charge cannot compensate for the negative total charge of the operator (the SUSY zero mechanism).

Higgs mass matrix becomes 7×7 matrix M_T which is given by

$$\begin{array}{c} \overline{D}^c \backslash D^c \\ \overline{\mathbf{10}}_{\overline{C}} \\ \mathbf{5}_{\overline{C}} \\ \mathbf{5}_{\overline{\Phi}} \\ \overline{\mathbf{10}}_{\overline{\Phi}'_1} \\ \overline{\mathbf{10}}_{\overline{\Phi}'_2} \\ \mathbf{5}_{\overline{\Phi}'_1} \\ \mathbf{5}_{\overline{\Phi}'_2} \end{array} \begin{array}{c} \begin{array}{ccccccc} \mathbf{10}_C & \bar{\mathbf{5}}_C & \bar{\mathbf{5}}_\Phi & \mathbf{10}_{\Phi'_1} & \mathbf{10}_{\Phi'_2} & \bar{\mathbf{5}}_{\Phi'_1} & \bar{\mathbf{5}}_{\Phi'_2} \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & \lambda^{\bar{c}+\phi'_1-\Delta} & \lambda^{\bar{c}+\phi'_2-\Delta} \\ 0 & 0 & 0 & \lambda^{\bar{c}+\phi'_1+\Delta} & \lambda^{\bar{c}+\phi'_2+\Delta} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda^{\bar{\phi}+\phi'_1} & \lambda^{\bar{\phi}+\phi'_2} \\ 0 & \lambda^{\bar{\phi}'_1+c-\Delta} & 0 & \lambda^{\bar{\phi}'_1+\phi'_1} & \lambda^{\bar{\phi}'_1+\phi'_2} & \lambda^{\bar{\phi}'_1+\phi'_1-\Delta} & \lambda^{\bar{\phi}'_1+\phi'_2-\Delta} \\ 0 & \lambda^{\bar{\phi}'_2+c-\Delta} & 0 & \lambda^{\bar{\phi}'_2+\phi'_1} & \lambda^{\bar{\phi}'_2+\phi'_2} & \lambda^{\bar{\phi}'_2+\phi'_1-\Delta} & \lambda^{\bar{\phi}'_2+\phi'_2-\Delta} \\ \lambda^{\bar{\phi}'_1+c+\Delta} & 0 & \lambda^{\bar{\phi}'_1+\phi} & \lambda^{\bar{\phi}'_1+\phi'_1+\Delta} & \lambda^{\bar{\phi}'_1+\phi'_2+\Delta} & \lambda^{\bar{\phi}'_1+\phi'_1} & \lambda^{\bar{\phi}'_1+\phi'_2} \\ \lambda^{\bar{\phi}'_2+c+\Delta} & 0 & \lambda^{\bar{\phi}'_2+\phi} & \lambda^{\bar{\phi}'_2+\phi'_1+\Delta} & \lambda^{\bar{\phi}'_2+\phi'_2+\Delta} & \lambda^{\bar{\phi}'_2+\phi'_1} & \lambda^{\bar{\phi}'_2+\phi'_2} \end{pmatrix} \end{array}, \tag{4.2}$$

where $\Delta \equiv \frac{1}{2}(\bar{\phi} - \phi - \bar{c} + c)$. The rank becomes seven for the charge assignment in Table 1. On the other hand, the mass matrix for doublet Higgs becomes 4×4 matrix. The charges in Table 1 lead to

$$M_D = \begin{array}{c} (\bar{L}'^*) \backslash \bar{L}' \\ \overline{C} \\ \overline{\Phi} \\ \overline{\Phi}'_1 \\ \overline{\Phi}'_2 \end{array} \begin{array}{c} \begin{array}{cccc} C & \Phi & \Phi'_1 & \Phi'_2 \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda^{\phi'_1+\bar{\phi}} & \lambda^{\phi'_2+\bar{\phi}} \\ 0 & \lambda^{\phi+\bar{\phi}'_1} & \lambda^{\phi'_1+\bar{\phi}'_1} & \lambda^{\phi'_2+\bar{\phi}'_1} \\ 0 & \lambda^{\phi+\bar{\phi}'_2} & \lambda^{\phi'_1+\bar{\phi}'_2} & \lambda^{\phi'_2+\bar{\phi}'_2} \end{pmatrix} \end{array}. \tag{4.3}$$

The rank can obviously be reduced to three, and therefore one pair of doublet Higgs appears in this model. The massless modes are written

$$H_u = (\bar{L}')_C, \tag{4.4}$$

$$H_d = (\bar{L}'^*)_{\overline{C}}, \tag{4.5}$$

where H_u and H_d are the doublet Higgs for the up quark sector and for the down quark sector, respectively.

4.2. Quark and lepton sector

This subsection uses the standard definition of $\bar{\mathbf{5}} \equiv (D^c, L)$ field. If three generation matter fields $\Psi_i(\mathbf{27}) = \mathbf{16}_{\Psi_i} + \mathbf{10}_{\Psi_i} + \mathbf{1}_{\Psi_i}$ $(i = 1, 2, 3)$ are introduced with their charges $(\psi_1, \psi_2, \psi_3) = (4, 3, 1)$ in addition to the Higgs sector in Table 1, the massless modes of $\bar{\mathbf{5}}$ fields, where the usual definition for $\bar{\mathbf{5}}$ was used, become

$$\begin{aligned} \bar{\mathbf{5}}_1 &= \bar{\mathbf{5}}'_{\Psi_1} + \lambda^3 \bar{\mathbf{5}}'_{\Psi_3} + \lambda^{1.5} \bar{\mathbf{5}}_{\Psi_2} + \lambda^{3.5} \bar{\mathbf{5}}_{\Psi_3}, \\ \bar{\mathbf{5}}_2 &= \bar{\mathbf{5}}_{\Psi_1} + \lambda^{2.5} \bar{\mathbf{5}}'_{\Psi_3} + \lambda^1 \bar{\mathbf{5}}_{\Psi_2} + \lambda^3 \bar{\mathbf{5}}_{\Psi_3}, \\ \bar{\mathbf{5}}_3 &= \bar{\mathbf{5}}'_{\Psi_2} + \lambda^2 \bar{\mathbf{5}}'_{\Psi_3} + \lambda^{0.5} \bar{\mathbf{5}}_{\Psi_2} + \lambda^{2.5} \bar{\mathbf{5}}_{\Psi_3}, \end{aligned} \tag{4.6}$$

where $\bar{\mathbf{5}}' \equiv (D^{c\prime}, L')$ and the three bases of the massless modes $(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2, \bar{\mathbf{5}}_3)$ are fixed to $(\bar{\mathbf{5}}'_{\Psi_1}, \bar{\mathbf{5}}_{\Psi_1}, \bar{\mathbf{5}}'_{\Psi_2})$. These are obtained from the mass matrix of three $\mathbf{5}$ fields and six $\bar{\mathbf{5}}$ fields as are given from the interactions $\Psi_i \Psi_j \Phi Z$ and $\Psi_i \Psi_j C$ by developing the VEVs of Φ, C and Z. Then the Yukawa couplings of quarks and leptons can be estimated.

The Yukawa couplings of the up quark sector are obtained as

$$Y_u = \begin{array}{c} \\ Q_{\Psi_1} \\ Q_{\Psi_2} \\ Q_{\Psi_3} \end{array} \begin{array}{c} \begin{array}{ccc} U^c_{\Psi_1} & U^c_{\Psi_2} & U^c_{\Psi_3} \end{array} \\ \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \end{array} \tag{4.7}$$

from the interactions $\lambda^{\psi_i+\psi_j+c}\mathbf{16}_{\Psi_i}\mathbf{10}_{\Psi_j}C$. The Yukawa couplings of the down quark sector and of the charged lepton sector are given as

$$Y_d^{\mathrm{T}}(\sim Y_e) = \begin{array}{c} \\ \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_2 \\ \bar{\mathbf{5}}_3 \end{array} \begin{array}{c} \begin{array}{ccc} Q_{\Psi_1}(E^c_{\Psi_1}) & Q_{\Psi_2}(E^c_{\Psi_2}) & Q_{\Psi_3}(E^c_{\Psi_3}) \end{array} \\ \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^{5.5} & \lambda^{4.5} & 0 \\ \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix} \end{array} \tag{4.8}$$

from the higher-dimensional interactions $\lambda^{\psi_i+\psi_j+2\bar{c}}\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\overline{C}\overline{C}$ and $\lambda^{\psi_i+\psi_j+2\bar{c}}\mathbf{10}_{\Psi_i}\mathbf{1}_{\Psi_j}\overline{C}\overline{C}$, respectively. The vanishing component is caused by SUSY zero (holomorphic zero). Note that only $\bar{\mathbf{5}}'$ fields can have non-vanishing Yukawa couplings through the interactions. This is because the interactions $\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\overline{C}\overline{\Phi}$ and $\mathbf{10}_{\Psi_i}\mathbf{1}_{\Psi_j}\overline{C}\overline{\Phi}$ are forbidden by Z_2-parity. The mass matrices above yield acceptable values for masses and mixings for the quark sector and charged lepton sector.

The Yukawa couplings for the Dirac neutrino are given as

$$Y_{n_D} = \begin{array}{c} \\ \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_2 \\ \bar{\mathbf{5}}_3 \end{array} \begin{array}{c} \begin{array}{cccccc} N^c_{\Psi_1} & N^c_{\Psi_2} & N^c_{\Psi_3} & S_{\Psi_1} & S_{\Psi_2} & S_{\Psi_3} \end{array} \\ \begin{pmatrix} \lambda^{6.5} & \lambda^{5.5} & \lambda^{3.5} & \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^6 & \lambda^5 & \lambda^3 & \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} & \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix} \end{array} \tag{4.9}$$

through the interactions $\lambda^{\psi_i+\psi_j+c}\mathbf{10}_{\Psi_i}\mathbf{16}_{\Psi_j}C$. The right-handed neutrino mass matrix becomes

$$M_{nR} = \begin{array}{c} \\ N^c_{\Psi_1} \\ N^c_{\Psi_2} \\ N^c_{\Psi_3} \\ S_{\Psi_1} \\ S_{\Psi_2} \\ S_{\Psi_3} \end{array} \begin{array}{c} \begin{array}{cccccc} N^c_{\Psi_1} & N^c_{\Psi_2} & N^c_{\Psi_3} & S_{\Psi_1} & S_{\Psi_2} & S_{\Psi_3} \end{array} \\ \begin{pmatrix} \lambda^8 & \lambda^7 & \lambda^5 & \lambda^{7.5} & \lambda^{6.5} & 0 \\ \lambda^7 & \lambda^6 & \lambda^4 & \lambda^{6.5} & 0 & 0 \\ \lambda^5 & \lambda^4 & 0 & 0 & 0 & 0 \\ \lambda^{7.5} & \lambda^{6.5} & 0 & \lambda^7 & \lambda^6 & \lambda^4 \\ \lambda^{6.5} & 0 & 0 & \lambda^6 & \lambda^5 & \lambda^3 \\ 0 & 0 & 0 & \lambda^4 & \lambda^3 & \lambda \end{pmatrix} \end{array} \Lambda \tag{4.10}$$

through the interactions $\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\overline{C}\overline{C}$, $\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\overline{C}\overline{\Phi}Z$ and $\mathbf{16}_{\Psi_i}\mathbf{16}_{\Psi_j}\overline{\Phi}\overline{\Phi}$. Here vanishing components are caused by the SUSY zero (holomorphic zero) mechanism. Then the neutrino mass matrix is given by

$$M_\nu = Y_{n_D} M_{nR}^{-1} Y_{n_D}^{\mathrm{T}} \langle H_u\rangle^2\eta^2 \sim \lambda^3 \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \frac{\langle H_u\rangle^2\eta^2}{\Lambda}, \tag{4.11}$$

where η is a renormalization factor. This yields bilarge neutrino mixings but to achieve the mass scale for the neutrino, the cutoff $\Lambda \sim 10^{13}$ GeV must be used if $\langle H_u\rangle\eta \sim 200$ GeV. Such a small cutoff scale leads to too short nucleon life-time via dimension six operators. Therefore, the charge assignment in Table 1 looks unrealistic.

However, because the neutrino scale is determined by the anomalous $U(1)_A$ charges as

$$M_\nu \sim \lambda^{-5-l} \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \frac{\langle H_u \rangle^2 \eta^2}{\Lambda}, \tag{4.12}$$

$$l = -2c + \bar{c} - 10, \tag{4.13}$$

there may be other realistic models with other charge assignments. To obtain a larger value of l, a smaller c and/or larger $\bar{c}$ is needed. Because C includes H_u, the charge c is determined as $c = -2\psi_3 = -2n$ so that the top Yukawa coupling becomes $O(1)$. Here, $\psi_i = \delta_i + n$ $[(\delta_1, \delta_2, \delta_3) = (3, 2, 0)]$ is used to obtain a realistic Cabbibo–Kobayashi–Maskawa matrix. To produce bilarge neutrino mixings (i.e., $\bar{\mathbf{5}}$ fields in Eq. (4.6)), the followings must hold:

$$\Delta = \frac{1}{2}[(c - \bar{c}) - (\phi - \bar{\phi})] \sim -\frac{1}{2}. \tag{4.14}$$

Once the mixing structure of $\bar{\mathbf{5}}$ fields is fixed, the Yukawa couplings for down quarks are proportional to $\lambda^{\psi_i + \psi_j + 2\bar{c}} \langle \overline{C} \rangle \sim \lambda^{\delta_i + \delta_j + \frac{3}{2}(\bar{c} - c)}$. Therefore, roughly speaking, $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$ is proportional to $\lambda^{\frac{3}{2}(\bar{c} - c)}$. Then, a smaller c and/or larger $\bar{c}$ lead to a smaller $\tan\beta$. For a fixed $\tan\beta$, a smaller c and $\bar{c}$ lead to a larger l. However, unless the condition

$$c - 2\bar{c} \leqslant 2 \tag{4.15}$$

is satisfied, $(Y_d)_{33}$ vanishes as a result of the SUSY zero mechanism. Here, a charge assignment

$$\left(\phi, \bar{\phi}, c, \bar{c}, \phi_i', \bar{\phi}_i', \bar{z}_i, z, s'\right) = (-1, -1, -4, -3, 8, 8, -1, -6, 12)$$

is proposed. Then l becomes -5, so the cutoff scale can be larger than the 10^{15} GeV. Actually, the running gauge couplings of $SU(3)_C$ and $SU(2)_L$, which should meet at the cutoff scale in this flipped $SO(10)$ scenario, meet around the scale in this charge assignment. And the Yukawa coupling of bottom quark becomes $\lambda^{3.5}$, which can be realistic, although the large ambiguity of $O(1)$ coefficients is required.

5. Summary

This Letter has shown that the missing partner mechanism in a flipped $SU(5)$ model can be embedded in a flipped $SO(10)$ model with a gauge group $SO(10)_F \times U(1)_{V_F'} \subset E_6$. Of interest is the fact that the gauge group includes $SU(2)_E$, which plays an important role in solving the SUSY flavor problem via the horizontal gauge symmetry and anomalous $U(1)_A$ gauge symmetry. As an existence proof, a specific flipped $SO(10)$ model was constructed by introduction of anomalous $U(1)_A$ gauge symmetry.

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