Embedding Flipped SU(5) into SO(10) Postprint

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Full Text

Preamble

Embedding Flipped SU(5) into SO(10)

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Abstract

We embed the flipped SU(5) models into SO(10) models. After the SO(10) gauge symmetry is broken down to the flipped SU(5) × $U(1)_X$ gauge symmetry, we can split the five/one-plets and ten-plets in the spinor 16 and $\overline{16}$ Higgs fields via the stable sliding singlet mechanism. As in the flipped SU(5) models, these ten-plet Higgs fields can break the flipped SU(5) gauge symmetry down to the Standard Model gauge symmetry. The doublet-triplet splitting problem can be solved naturally by the missing partner mechanism, and the Higgsino-exchange mediated proton decay can be suppressed elegantly. Moreover, we show that there exists one pair of light Higgs doublets for electroweak gauge symmetry breaking. Because there exist two pairs of additional vector-like particles with similar intermediate-scale masses, the SU(5) and $U(1)_X$ gauge couplings can be unified at the GUT scale which is reasonably (about one or two orders) higher than the $SU(2)_L\times$ $SU(3)_C$ unification scale. Furthermore, we briefly discuss the simplest SO(10) model with flipped SU(5) embedding, and point out that it cannot work without fine-tuning.

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Introduction

The gauge hierarchy problem is one of the main motivations to study physics beyond the Standard Model (SM). The Higgs boson is needed in the SM to break electroweak gauge symmetry and give masses to SM fermions, and the breaking scale is directly related to the Higgs boson mass. However, in quantum field theory, fermionic masses can be protected against quantum corrections by chiral symmetry, while no such symmetry exists for bosonic masses. The Higgs boson mass (squared) has a quadratic divergence at one loop, making it unnatural to maintain a stable weak scale hierarchically smaller than the Planck scale. An additional aesthetic motivation for physics beyond the SM comes from Grand Unified Theories (GUTs), which can unify all known gauge interactions and provide a simple understanding of the quantum numbers of SM fermions.

Supersymmetry provides an elegant solution to the gauge hierarchy problem. The success of gauge coupling unification in the Minimal Supersymmetric Standard Model (MSSM) strongly supports the possibility of supersymmetric GUTs [?, ?, ?, ?, ?, ?]. Other appealing features of supersymmetric GUTs include electroweak gauge symmetry breaking by radiative corrections due to the large top quark Yukawa coupling, and the natural generation of tiny neutrino masses via the see-saw mechanism [?, ?, ?, ?]. Therefore, supersymmetric GUTs are promising candidates that can describe all known fundamental interactions in nature except gravity. However, four-dimensional supersymmetric GUTs face severe problems, particularly the doublet-triplet splitting problem and the proton decay problem.

Among known supersymmetric GUTs, only the flipped SU(5) models can naturally explain doublet-triplet splitting via a simple and elegant missing partner mechanism [?, ?, ?, ?]. The Higgsino-exchange mediated proton decay problem, which plagues other supersymmetric GUTs, is solved automatically. However, the gauge group of flipped SU(5) models is the product group SU(5) × U(1)$_X$, not a simple group, so the unifications of gauge interactions and their couplings are not "grand." Consequently, SM fermions in each family do not sit in a single representation of the gauge group, unlike in the SO(10) model.

In flipped SU(5) models, since the masses of down-type quarks and charged leptons arise from different Yukawa couplings, the bottom quark mass is generically not equal to the τ lepton mass at the GUT scale, contrary to predictions in other supersymmetric GUTs such as SU(5). The grand unification of gauge interactions and the unification of each family of SM fermions into a single representation can be achieved by embedding flipped SU(5) into SO(10). However, it is well-known that the missing partner mechanism cannot work because the partners missing in the SU(5) × U(1)$_X$ multiplets indeed appear in the larger SO(10) multiplets. To solve this problem, two kinds of models have been proposed: five-dimensional orbifold SO(10) models [?], and four-dimensional SO(10) × SO(10) models with bi-spinor link Higgs fields [?] (for other SO(10) models with flipped SU(5) embedding, see Refs. [?, ?]).

In this paper, we embed flipped SU(5) models into four-dimensional SO(10) models where the missing partner mechanism can still work elegantly. In flipped SU(5) models, the Higgs fields H and $\bar{H}$, which break flipped SU(5) gauge symmetry down to SM gauge symmetry, are a pair of vector-like fields in the $(\mathbf{10}, \mathbf{1})$ and $(\mathbf{10}, -\mathbf{1})$ representations of SU(5) × U(1)$_X$, respectively. When we embed flipped SU(5) into SO(10), these Higgs fields H and $\bar{H}$ are embedded into the Higgs fields Σ and $\bar{\Sigma}$ in the spinor $\mathbf{16}$ and $\bar{\mathbf{16}}$ representations of SO(10). The missing partners for the MSSM Higgs doublets H_u and H_d belong to the $(\mathbf{5}, -\mathbf{3})$ and $(\bar{\mathbf{5}}, \mathbf{3})$ of Σ and $\bar{\Sigma}$ when we decompose the SO(10) spinor representations into SU(5) × U(1)$_X$ representations (for detailed decompositions see Appendix A). Also, in flipped SU(5) models, the Higgs fields h and $\bar{h}$, which include the Higgs doublets H_u and H_d, are in $(\mathbf{5}, -2)$ and $(\bar{\mathbf{5}}, 2)$ representations, respectively. Interestingly, the Higgs fields h and $\bar{h}$ in our models can form a $\mathbf{10}$ representation Higgs field h_{10} of SO(10). Note that we will break the SO(10) gauge symmetry down to flipped SU(5) gauge symmetry at the GUT scale $M_{\rm GUT}$, and further down to SM gauge symmetry at the SU(2)$_L$× SU(3)$_C$ unification scale M_{23}. To achieve successful doublet-triplet splitting via the missing partner mechanism, we must split the five-plets and ten-plets in Σ and $\bar{\Sigma}$—the five-plets in Σ and $\bar{\Sigma}$ must have masses around $M_{\rm GUT}$ while the corresponding ten-plets should remain massless after SO(10) gauge symmetry breaking.

We construct three-family SO(10) models with two adjoint Higgs fields Φ and Φ', Σ, $\bar{\Sigma}$, h_{10}, one pair of spinor $\mathbf{16}$ and $\bar{\mathbf{16}}$ representations χ and $\bar{\chi}$, and several singlets. After SO(10) gauge symmetry is broken down to flipped SU(5) gauge symmetry, the five/one-plets and ten-plets in the multiplets χ and Σ, and $\bar{\Sigma}$ and $\bar{\chi}$ can be split via the sliding singlet mechanism, which we show to be stable. Similar to flipped SU(5) models, we can break the gauge symmetry down to SM gauge symmetry by giving vacuum expectation values (VEVs) to the neutral singlet components of H and $\bar{H}$. Doublet-triplet splitting can be realized by the simple missing partner mechanism, and Higgsino-exchange mediated proton decay is negligible.

Moreover, we show that there exists one pair of light Higgs doublets mainly from H_u and H_d for electroweak gauge symmetry breaking. Since there exist two pairs of vector-like particles (mainly from the corresponding components in χ and $\bar{\chi}$) with roughly the same intermediate-scale masses whose SM quantum numbers are $(\mathbf{3}, \mathbf{1}, 1/3) + (\bar{\mathbf{3}}, \mathbf{1}, -1/3)$, $(\mathbf{3}, \mathbf{2}, 1/6)$, $(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$, the SU(5) $\times$ U$(1)_X$ gauge coupling unification can be achieved at the GUT scale which is reasonably (about one or two orders) higher than the SU$(2)_L \times$ SU$(3)_C$ unification scale [**?**, **?**]. Therefore, we can keep the beautiful features and eliminate the drawbacks of flipped SU(5) models in our SO(10) models.

Furthermore, we briefly consider the simplest SO(10) model with flipped SU(5) embedding, and point out that it cannot work without fine-tuning. We also explain how to generate the suitable vector-like mass for χ and $\bar{\chi}$.

This paper is organized as follows: in Section II we briefly review flipped SU(5) models and the sliding singlet mechanism. We present our SO(10) models in Section III. We consider mixings between light and superheavy particles, and study gauge coupling unification in Section IV. Our remarks on the simplest SO(10) model and the vector-like mass for χ and $\bar{\chi}$ are given in Section V. Section VI contains our discussion and conclusions. We present the SO(10) generators in the spinor representations in Appendix A.

Brief Review

In this section, we briefly review flipped SU(5) models [**?**, **?**] and the sliding singlet mechanism [**?**].

A. The Flipped SU(5) Models

First, let us consider flipped SU(5) models [**?**, **?**]. We can define the generator U$(1)_{Y'}$ in SU(5) as $T_{U(1)_{Y'}} \equiv \mathrm{diag}(2, 2, 2, -3, -3)$ and the hypercharge is given by $(Q_X - Q_{Y'})$.

There are three families of SM fermions with the following SU(5) $\times$ U$(1)_X$ quantum numbers: $F_i = (\mathbf{10}, 1)$, $\bar{f}_i = (\bar{\mathbf{5}}, -3)$, $\bar{l}_i = (\mathbf{1}, 5)$, where $i = 1, 2, 3$. As an example, the particle assignments for the first family are:

$$F_1 = (Q_1, D_1^c, N_1^c), \quad \bar{f}_1 = (U_1^c, L_1), \quad \bar{l}_1 = E_1^c$$

where Q and L are respectively the superfields of the left-handed quark and lepton doublets, and U^c, D^c, E^c and N^c are the CP-conjugated superfields for the right-handed up-type quark, down-type quark, lepton and neutrino, respectively. In addition, to give heavy masses to right-handed neutrinos, we add three singlets ϕ_i.

To break the GUT and electroweak gauge symmetries, we introduce two pairs of vector-like Higgs fields:

$$H = (\mathbf{10}, 1), \quad \bar{H} = (\bar{\mathbf{10}}, -1), \quad h = (\mathbf{5}, -2), \quad \bar{h} = (\bar{\mathbf{5}}, 2).$$

We label the states in the H multiplet by the same symbols as in the F multiplet, and for $\bar{H}$ we just add a "bar" above the fields. Explicitly, the Higgs particles are:

$$H = (Q_H, D^c_H, N^c_H), \quad \bar{H} = (\bar{Q}_H, \bar{D}_H, \bar{N}_H), \quad h = (D_h, D_h, D_h, H_d), \quad \bar{h} = (\bar{D}_h, \bar{D}_h, \bar{D}_h, H_u)$$

where H_d and H_u are the two Higgs doublets in the MSSM.

To break the SU(5) × U(1)$_X$ gauge symmetry down to SM gauge symmetry, we introduce the superpotential:

$$W = \lambda_1 HHh + \lambda_2 \bar{H}\bar{H}\bar{h} + S(H\bar{H} - M_H^2)$$

where S is a singlet, and λ_1 and λ_2 are Yukawa couplings. There is only one F-flat and D-flat direction, which can always be rotated along the N^c_H directions. So we obtain $\langle N^c_H \rangle = \langle \bar{N}_H \rangle = M_H$.

In addition, the superfields H and $\bar{H}$ are eaten and acquire large masses via the Higgs mechanism with supersymmetry, except for D^c_H and $\bar{D}_H$. The superpotential terms $\lambda_1 HHh$ and $\lambda_2 \bar{H}\bar{H}\bar{h}$ combine D^c_H with D_h and $\bar{D}_H$ with $\bar{D}_h$, respectively, to form massive eigenstates with masses $2\lambda_1 \langle N^c_H \rangle$ and $2\lambda_2 \langle \bar{N}_H \rangle$. Since there are no partners in H and $\bar{H}$ for H_u and H_d, we naturally obtain doublet-triplet splitting due to the missing partner mechanism. Because the triplets in h and $\bar{h}$ only have small mixing through the μ term, Higgsino-exchange mediated proton decay is negligible, i.e., we do not have the dimension-5 proton decay problem.

The SM fermion masses arise from the superpotential:

$$W_{\text{Yukawa}} = y^D_{ij} F_i F_j h + y^U_{ij} F_i \bar{f}_j \bar{h} + y^E_{ij} \bar{l}_i \bar{f}_j h + \mu h\bar{h} + y^N_{ij} \phi_i \bar{H} F_j,$$

where y^D_{ij}, y^U_{ij}, y^E_{ij} and y^N_{ij} are Yukawa couplings, and μ is the bilinear Higgs mass term.

After SU(5) × U(1)$_X$ gauge symmetry is broken down to SM gauge symmetry, the above superpotential gives:

$$W_{\text{SSM}} = y^D_{ij} D^c_i Q_j H_d + y^U_{ij} U^c_i Q_j H_u + y^E_{ij} E^c_i L_j H_d + y^U_{ij} N^c_i L_j H_u + \mu H_d H_u + y^N_{ij} \langle N^c_H \rangle \phi_i N^c_j + \cdots \text{(decoupled below } M_{\text{GU}}$$

B. Sliding Singlet Mechanism

The sliding singlet mechanism was originally proposed in the supersymmetric SU(5) model [?], where the Higgs superpotential is:

$$W = W(\Phi) + \bar{H}_5(\Phi + S)H_5,$$

where Φ is an SU(5) adjoint Higgs field, S is a SM singlet, and $\bar{H}_5$ and H_5 are the anti-fundamental and fundamental Higgs fields which respectively contain one pair of Higgs doublets H_d and H_u.

With a suitable superpotential $W(\Phi)$ for Φ, one assumes that Φ obtains the VEV:

$$\langle\Phi\rangle = \mathrm{diag}(2, 2, 2, -3, -3)V_\Phi.$$

Then the SU(5) gauge symmetry is broken down to SM gauge symmetry.

The F-flatness conditions for the F-terms of H_5 and $\bar{H}_5$, valid at a supersymmetric minimum, give:

$$(\langle\Phi\rangle + \langle S\rangle)\langle H_5\rangle = 0, \quad \langle\bar{H}_5\rangle(\langle\Phi\rangle + \langle S\rangle) = 0.$$

To break electroweak gauge symmetry, the Higgs doublets H_d and H_u are supposed to obtain VEVs around the electroweak scale. From F-flatness conditions $F_{H_d} = F_{H_u} = 0$, we obtain:

$$\langle S\rangle = -\frac{V_\Phi}{2}.$$

Therefore:

$$\langle\Phi\rangle + \langle S\rangle = \mathrm{diag}\left(\frac{5}{2}, \frac{5}{2}, \frac{5}{2}, 0, 0\right) V_\Phi.$$

As a result, the color triplets in $\bar{H}_5$ and H_5 obtain vector-like mass around V_Φ, while the doublets remain massless after SU(5) gauge symmetry breaking. Because the singlet slides to cancel off the VEV of the adjoint Higgs field in the $SU(2)_L$ block, this mechanism is called the sliding singlet mechanism.

However, the sliding singlet mechanism for supersymmetric SU(5) models breaks down due to supersymmetry breaking [**?**]. The potential from the F-terms of $\bar{H}_5$ and H_5 only gives electroweak-scale mass $((\langle H_d^0\rangle)^2 + (\langle H_u^0\rangle)^2)$ to S, while soft supersymmetry breaking gives S mass around the supersymmetry breaking scale M_S. However, S couples to triplets in $\bar{H}_5$ and H_5 with masses around the GUT scale, so one-loop tadpole graphs with triplets running around the loop induce the following terms in the low-energy effective theory that destroy the doublet-triplet splitting:

$$T_1 = \mathcal{O}(m_g M_{\mathrm{GUT}})S + \mathrm{h.c.}, \quad T_2 = \mathcal{O}(m_g M_{\mathrm{GUT}})F_S + \mathrm{h.c.},$$

where m_g is the gravitino mass, usually around M_S.

The T_1 term shifts the VEV of S from its supersymmetric minimum $-V_\Phi/2$ by:

$$\delta\langle S\rangle \sim \frac{\mathcal{O}(m_g M_{\mathrm{GUT}})}{(\langle H_d^0\rangle)^2 + (\langle H_u^0\rangle)^2} \sim \mathcal{O}(M_{\mathrm{GUT}}),$$

and then the doublets in $\bar{H}_5$ and H_5 obtain vector-like mass around the GUT scale.

In addition, after integrating out the auxiliary field F_S, the T_2 term gives:

$$V \supset |\bar{H}_5 H_5 + \mathcal{O}(m_g M_{\rm GUT})|^2.$$

Thus, the VEVs of H_d^0 and H_u^0 are around the scale $m_g M_{\rm GUT}$, inconsistent with the known value $(\langle H_d^0\rangle)^2 + (\langle H_u^0\rangle)^2 \simeq 246.2$ GeV.

In gauge-mediated supersymmetry breaking scenarios, the gravitino mass can be very light (below the keV scale), but the sliding singlet mechanism may still not work [**?**].

The sliding singlet mechanism can be successfully applied to rank-five or higher GUT groups [**?**, **?**, **?**], such as SU(6) and E_6 models. The key is that the corresponding Higgs fields like $\bar{H}_5$ and H_5 in the SU(5) model can have very large or GUT-scale VEVs. Let us briefly comment on SU(6) models. To maintain F-flatness and have one pair of light Higgs doublets, we need at least three pairs of vector-like particles in the SU(6) fundamental **6** and anti-fundamental $\bar{\mathbf{6}}$ representations. In known models, there are four pairs of such particles [**?**].

SO(10) Models

We construct SO(10) models where gauge symmetry is broken down to flipped SU(5) gauge symmetry by giving VEVs to adjoint Higgs fields, and further down to SM gauge symmetry by giving VEVs to H and $\bar{H}$. We denote the SM fermions as ψ_i which form the spinor **16** representation. We introduce two adjoint **45** representation Higgs fields Φ and Φ', one pair of spinor **16** and $\bar{\mathbf{16}}$ representation Higgs fields Σ and $\bar{\Sigma}$, one **10** representation Higgs field h_{10}, one pair of spinor **16** and $\bar{\mathbf{16}}$ representation vector-like particles χ and $\bar{\chi}$, and nine singlets ϕ_i, S, S', S_i, and S_Σ where $i = 1, 2, 3$. The complete particle content is given in Table I.

In terms of particles in flipped SU(5) models, we have:

$$\psi_i = (F_i, \bar{f}_i, \bar{l}_i); \quad h_{10} = (h, \bar{h}).$$

In our convention, for one pair of spinor **16** and $\bar{\mathbf{16}}$ representation chiral superfields K and $\bar{K}$, we denote their components like SM fermions as follows:

TABLE I: Particle content in SO(10) models.

Representation	Chiral Superfields
45	Φ, Φ'
16	ψ_i, Σ, χ
10	h_{10}
1	ϕ_i, S, S', S_i, S_Σ

where:

$$K_F = (Q_K, D_K^c), \quad \bar{K}_F = (\bar{Q}_K, \bar{D}_K, \bar{N}_K), \quad K_f = (U_K^c, L_K), \quad \bar{K}_{\bar{f}} = (U_K, \bar{L}_K).$$

The only exception is that, similar to flipped SU(5) models, we denote the Higgs fields Σ_F and $\bar{\Sigma}_F$ as H and $\bar{H}$, respectively. To be concrete:

$$\Sigma = (H, \Sigma_{\bar{f}}, \Sigma_{\bar{l}}), \quad \bar{\Sigma} = (\bar{H}, \Sigma_f, \Sigma_l).$$

The superpotential is:

$$\begin{aligned} W =& W(\Phi, \Phi') + W(\Sigma, \bar{\Sigma}) + y_{ij}\psi_i h_{10}\psi_j + y_{ij}^N \phi\Sigma\psi_j + \mu h_{10}h_{10} \\ &+ \lambda_1 \Sigma h_{10}\Sigma + \lambda_2 \bar{\Sigma} h_{10}\bar{\Sigma} + \lambda_3 \chi(\Phi + \lambda_4 S)\Sigma \\ &+ \lambda_5 \bar{\Sigma}(\Phi' + \lambda_6 S')\bar{\chi} + M_\chi \chi\bar{\chi}, \end{aligned}$$

where y_{ij}, y_{ij}^N, and λ_i $(i = 1, 2, \ldots, 6)$ are Yukawa couplings, and μ and M_χ are vector-like masses. The general superpotential $W(\Phi, \Phi')$ for Φ and Φ', and the simple superpotential $W(\Sigma, \bar{\Sigma})$ for Σ and $\bar{\Sigma}$ are:

$$\begin{aligned} W(\Phi, \Phi') =& \kappa\Phi^3 + M_\Phi \Phi^2 + \lambda_7 S_1(\Phi^2 - m_{11}^2) + M_{\Phi\Phi'}\Phi\Phi' \\ &+ \lambda_8 S_3(\Phi\Phi' - m_{12}^2) + \kappa'\Phi'^3 + M_{\Phi'}\Phi'^2 + \lambda_7' S_2(\Phi'^2 - m_{22}^2), \\ W(\Sigma, \bar{\Sigma}) =& S_2\Sigma(\bar{\Sigma}\Sigma - M_H^2), \end{aligned}$$

where κ, κ', λ_7, λ_7', and λ_8 are Yukawa couplings, and M_Φ, $M_{\Phi'}$, $M_{\Phi\Phi'}$, m_{11}, m_{22}, m_{12}, and M_H are mass parameters.

Let us briefly comment on $W(\Phi, \Phi')$. First, we must have at least one term coupling Φ and Φ' so that we only have one global SO(10) symmetry in $W(\Phi, \Phi')$—the SO(10) gauge symmetry. Otherwise, we would have unwanted massless Nambu-Goldstone bosons. Second, some Yukawa couplings and mass parameters in $W(\Phi, \Phi')$ should be zero. For example, m_{11}, m_{22}, and m_{12} cannot all be non-zero, otherwise we would need to fine-tune these masses to satisfy the F-flatness conditions $F_{S_i} = 0$. Let us present a simple $W(\Phi, \Phi')$:

$$W(\Phi, \Phi') = M_{\Phi\Phi'}\Phi\Phi' + \lambda_8 S_3(\Phi\Phi' - m_{12}^2).$$

The flatness of the F-term of S_3 ($F_{S_3} = 0$) implies $\langle\Phi\rangle \neq 0$ and $\langle\Phi'\rangle \neq 0$. Also, the F-flatness conditions for Φ and Φ' ($F_\Phi = F_{\Phi'} = 0$) imply $\langle\Phi\rangle = \langle\Phi'\rangle \neq 0$ and $\langle S_3\rangle \neq 0$. By the way, at very high temperature, the SO(10) gauge symmetry will be restored when we consider the superpotential at finite temperature.

The gauge fields of SO(10) are in the adjoint representation of SO(10) with dimension **45**. Under the gauge group SU(5) × U(1)$_X$, the SO(10) gauge fields decompose as [**?**]:

$$\mathbf{45} = (\mathbf{24}, 0) \oplus (\mathbf{10}, -4) \oplus (\bar{\mathbf{10}}, 4) \oplus (\mathbf{1}, 0).$$

To break SO(10) gauge symmetry down to flipped SU(5) gauge symmetry via adjoint Higgs fields, we need to give VEVs to their singlet components.

As explained in the Introduction, to achieve doublet-triplet splitting via the missing partner mechanism, we must split the five/one-plets and ten-plets in Σ

and $\bar{\Sigma}$. To give GUT-scale masses to $\Sigma_{\bar{f}}$, $\Sigma_{\bar{l}}$, Σ_f and Σ_l while keeping H and $\bar{H}$ massless when we break SO(10) gauge symmetry down to flipped SU(5) gauge symmetry, we should express the SO(10) generators in the spinor representations which are 16×16 matrices given in Appendix A. Note that when the $\mathrm{U}(1)_X$ generator $T_{U(1)_X}$ acts on the spinor representation **16**, it gives the corresponding $\mathrm{U}(1)_X$ charges of the particles belonging to **16**. So we obtain the generator for $\mathrm{U}(1)_X$:

$$T_{U(1)_X} = \mathrm{diag}(1, 1, 1, -3, 1, 1, 1, -3, 1, 1, 1, 5, -3, -3, -3, 1).$$

For simplicity, we assume that Φ and Φ' obtain VEVs at the GUT scale due to the superpotential $W(\Phi, \Phi')$, and the F-flatness conditions for Φ, Φ' and S_i are satisfied by choosing suitable Yukawa couplings and mass parameters in $W(\Phi, \Phi')$. The explicit VEVs for Φ and Φ' are:

$$\langle\Phi\rangle = \mathrm{diag}(1, 1, 1, -3, 1, 1, 1, -3, 1, 1, 1, 5, -3, -3, -3, 1)V_\Phi,$$
$$\langle\Phi'\rangle = \mathrm{diag}(1, 1, 1, -3, 1, 1, 1, -3, 1, 1, 1, 5, -3, -3, -3, 1)V_{\Phi'},$$

where V_Φ and $V_{\Phi'}$ are around the GUT scale.

The F-flatness conditions for χ and $\bar{\chi}$, valid at a supersymmetric minimum, give:

$$(\langle\Phi\rangle + \lambda_4\langle S\rangle)\langle\Sigma\rangle = 0, \quad \langle\bar{\Sigma}\rangle(\langle\Phi'\rangle + \lambda_6\langle S'\rangle) = 0.$$

To break flipped SU(5) gauge symmetry down to SM gauge symmetry, we give VEVs to $N_H^c \subset H \subset \Sigma$ and $\bar{N}_H \subset \bar{H} \subset \bar{\Sigma}$ at the $\mathrm{SU}(3)_C\times \mathrm{SU}(2)_L$ unification scale M_{23}, which is around 3.7×10^{16} GeV. From the F-flatness conditions $F_{N_H^c} = F_{\bar{N}_H} = 0$, we obtain:

$$\langle S\rangle = -\frac{\langle N_H^c\rangle}{\lambda_4}, \quad \langle S'\rangle = -\frac{\langle\bar{N}_H\rangle}{\lambda_6}.$$

Thus:

$$\langle\Phi\rangle + \lambda_4\langle S\rangle = \mathrm{diag}(0, 0, 0, -4, 0, 0, 0, -4, 0, 0, 0, 4, -4, -4, -4, 0)V_\Phi,$$
$$\langle\Phi'\rangle + \lambda_6\langle S'\rangle = \mathrm{diag}(0, 0, 0, -4, 0, 0, 0, -4, 0, 0, 0, 4, -4, -4, -4, 0)V_{\Phi'}.$$

Then we have the following vector-like mass terms for the pairs (χ_f, Σ_f), (χ_l, Σ_l), $(\Sigma_f, \bar{\chi}_f)$, and $(\Sigma_l, \bar{\chi}_l)$:

$$V \supset -4\lambda_3 V_\Phi \chi_f \Sigma_f - \chi_l \Sigma_l - 4\lambda_5 V_{\Phi'} \Sigma_f \bar{\chi}_f - \Sigma_l \bar{\chi}_l,$$

where for simplicity we neglect M_χ, which will be shown to be very small compared to M_{GUT} and M_{23} so that we can have one pair of light Higgs doublets for electroweak gauge symmetry breaking. However, the particles χ_F, H, $\bar{H}$ and $\bar{\chi}_F$ are massless if we neglect M_χ. Thus, we split the five/one-plets and ten-plets in the multiplets χ and Σ, and $\bar{\Sigma}$ and $\bar{\chi}$ via the sliding singlet mechanism after breaking SO(10) gauge symmetry down to flipped SU(5) gauge symmetry.

As discussed in the brief review of flipped SU(5) models, we break SU(5) $\times$ U(1)$_X$ gauge symmetry down to SM gauge symmetry by giving VEVs to N^c_H and $\bar{N}_H$ of H and $\bar{H}$. The superfields H and $\bar{H}$ are eaten and acquire large masses via the Higgs mechanism with supersymmetry, except for D^c_H and $\bar{D}_H$. The superpotential terms $\lambda_1 HHh \subset \lambda_1 \Sigma h_{10} \Sigma$ and $\lambda_2 \bar{H}\bar{H}\bar{h} \subset \lambda_2 \bar{\Sigma} h_{10} \bar{\Sigma}$ combine D^c_H with D_h and $\bar{D}_H$ with $\bar{D}_h$, respectively, to form massive eigenstates with masses $2\lambda_1 \langle N^c_H \rangle$ and $2\lambda_2 \langle \bar{N}_H \rangle$. So we solve the doublet-triplet splitting problem naturally via the missing partner mechanism. Because the triplets in h and $\bar{h}$ of h_{10} only have small mixing through the μ term, Higgsino-exchange mediated proton decay is negligible, i.e., we do not have the dimension-5 proton decay problem.

Let us show that our sliding singlet mechanism is stable. The T_1-type tadpoles shift the VEVs of S and S' from their supersymmetric minima by:

$$\delta\langle S \rangle \sim \frac{\mathcal{O}(m_g M_{\rm GUT})}{4(\langle N^c_H \rangle)^2}, \quad \delta\langle S' \rangle \sim \frac{\mathcal{O}(m_g M_{\rm GUT})}{4(\langle \bar{N}_H \rangle)^2}.$$

These shifting effects are tiny and can be neglected.

Moreover, after integrating out the auxiliary fields F_S and $F_{S'}$, the T_2-type tadpoles give:

$$V \supset |\lambda_3 \lambda_4 \chi \Sigma + \mathcal{O}(m_g M_{\rm GUT})|^2 + |\lambda_5 \lambda_6 \bar{\Sigma} \bar{\chi} + \mathcal{O}(m_g M_{\rm GUT})|^2.$$

Then we obtain:

$$\langle N^c_\chi \rangle \sim -\frac{\mathcal{O}(m_g M_{\rm GUT})}{\lambda_3 \lambda_4 \langle N^c_H \rangle}, \quad \langle \bar{N}_\chi \rangle \sim -\frac{\mathcal{O}(m_g M_{\rm GUT})}{\lambda_5 \lambda_6 \langle \bar{N}_H \rangle}.$$

Because Σ and $\bar{\Sigma}$, or χ and $\bar{\chi}$ do not contain the pair of Higgs doublets H_d and H_u in the MSSM, it is fine to have very small non-zero VEVs for N^c_χ and $\bar{N}_\chi$ compared to $M_{\rm GUT}$ and M_{23}.

Moreover, from the F-flatness conditions for χ and $\bar{\chi}$, we obtain:

$$\langle \Phi \rangle + \lambda_4 \langle S \rangle \sim \frac{\mathcal{O}(m_g M_{\rm GUT})}{\lambda_3 \lambda_5 \lambda_6 \langle N^c_H \rangle \langle \bar{N}_H \rangle} M_\chi,$$
$$\langle \Phi' \rangle + \lambda_6 \langle S' \rangle \sim \frac{\mathcal{O}(m_g M_{\rm GUT})}{\lambda_3 \lambda_4 \lambda_5 \langle N^c_H \rangle \langle \bar{N}_H \rangle} M_\chi.$$

Thus, the variations in $\langle \Phi \rangle + \lambda_4 \langle S \rangle$ and $\langle \Phi' \rangle + \lambda_6 \langle S' \rangle$ are very small compared to $M_{\rm GUT}$ and M_{23}, and will not affect the splittings of five/one-plets and ten-plets in χ, Σ, $\bar{\Sigma}$ and $\bar{\chi}$. Especially for gauge-mediated supersymmetry breaking, the gravitino mass can be around the keV scale, making these variations completely negligible. Therefore, our sliding singlet mechanism is stable. By the way, the

VEVs of Φ, S, Φ', S', N_H^c and $\bar{N}_H$ will be shifted by tiny amounts due to non-zero $\langle N_\chi^c\rangle$ and $\langle \bar{N}_\chi\rangle$, but we will neglect these VEVs in the following discussions as they are very small compared to V_Φ, $V_{\Phi'}$, $\langle N_H^c\rangle$, and $\langle \bar{N}_H\rangle$.

Phenomenological Consequences

In this section, we study mixings between light and superheavy particles, and gauge coupling unification.

A. Light and Superheavy Particle Mixings

After flipped SU(5) gauge symmetry breaking, the possible light particles are three families of SM fermions, one pair of Higgs doublets H_d and H_u, and one pair of **10** representation χ_F and $\bar{\mathbf{10}}$ representation $\bar{\chi}_F$ in χ and $\bar{\chi}$. However, to ensure that H_d, H_u, χ_F and $\bar{\chi}_F$ are indeed light, we must calculate all possible mixing mass matrices between these particles and superheavy particles.

There are three types of relevant particle mixings:

1. **(X, Y)-type particle mixings**: In SU(5) language, the doublets (X, Y)- and $(\bar{X}, \bar{Y})$-type particles in the $(\mathbf{24}, 0)$ decomposed representations of Φ and Φ' have the same SM quantum numbers as the quark doublet and its Hermitian conjugate. After N_H^c and $\bar{N}_H$ obtain VEVs, they mix with Q_χ and $\bar{Q}_\chi$ in χ_F and $\bar{\chi}_F$. Let us denote the (X, Y)- and $(\bar{X}, \bar{Y})$-type particles in Φ as Q_Φ and $\bar{Q}_\Phi$, and in Φ' as $Q_{\Phi'}$ and $\bar{Q}_{\Phi'}$. The mass terms in the superpotential are:

   $$W \supset M_{XY}^{11} Q_\Phi \bar{Q}_\Phi + M_{XY}^{12} Q_\Phi \bar{Q}_{\Phi'} + M_{XY}^{21} Q_{\Phi'} \bar{Q}_\Phi + M_{XY}^{22} Q_{\Phi'} \bar{Q}_{\Phi'} + \lambda_3 \langle N_H^c\rangle Q_\chi \bar{Q}_\Phi + \lambda_5 \langle \bar{N}_H\rangle Q_{\Phi'} \bar{Q}_\chi + M_\chi Q_\chi \bar{Q}_\chi$$

   where M_{XY}^{ij} are mass parameters around the GUT scale. The corresponding mass matrix for the basis $(Q_\Phi, Q_{\Phi'}, Q_\chi)^t$ versus $(\bar{Q}_\Phi, \bar{Q}_{\Phi'}, \bar{Q}_\chi)$ is:

   $$M_{QQ}^{XY} = \begin{pmatrix} M_{XY}^{11} & M_{XY}^{12} & \lambda_3 \langle N_H^c\rangle \\ M_{XY}^{21} & M_{XY}^{22} & 0 \\ 0 & \lambda_5 \langle \bar{N}_H\rangle & M_\chi \end{pmatrix}.$$

   The determinant of this mass matrix is:

   $$\det[M_{QQ}^{XY}] = (M_{XY}^{11} M_{XY}^{22} - M_{XY}^{12} M_{XY}^{21}) M_\chi \sim M_{\mathrm{GUT}}^2 M_\chi,$$

   assuming no fine-tuning. So there are two pairs of vector-like particles (major components belonging to Q_Φ, $\bar{Q}_\Phi$, $Q_{\Phi'}$, $\bar{Q}_{\Phi'}$) with vector-like masses around the GUT scale, and one pair of vector-like particles (major components belonging to Q_χ, $\bar{Q}_\chi$) with vector-like mass around M_χ.

2. **SM singlet mixings**: For Φ and Φ', we consider the SU(5) $\times$ U(1)$_X$ singlets as given in Eq. (27), corresponding to U(1)$_X$ gauge field components. We denote the singlets in Φ and Φ' as S_Φ and $S_{\Phi'}$. After flipped

SU(5) gauge symmetry breaking, we have mass terms:

$$W \supset M_{SX}^{11} S_\Phi S_{\Phi'} + M_{SX}^{12} S_\Phi S' + M_{SX}^{21} S S_{\Phi'} + \lambda_3 \langle N_H^c \rangle (S_\Phi + \lambda_4 S) N_\chi^c + \lambda_5 \langle \bar{N}_H \rangle (S_{\Phi'} + \lambda_6 S') \bar{N}_\chi + M_\chi N_\chi^c \bar{N}_\chi,$$

where M_{SX}^{ij} are mass parameters around the GUT scale. The corresponding mass matrix for the basis $(S_\Phi, S, S_{\Phi'}, S', N_\chi^c)$ is:

$$M_{\text{singlets}} = \begin{pmatrix} 0 & M_{SX}^{11} & M_{SX}^{12} & 0 & \lambda_3 \langle N_H^c \rangle \\ M_{SX}^{11} & 0 & M_{SX}^{21} & 0 & \lambda_3 \lambda_4 \langle N_H^c \rangle \\ M_{SX}^{12} & M_{SX}^{21} & 0 & \lambda_5 \langle \bar{N}_H \rangle & 0 \\ 0 & 0 & \lambda_5 \langle \bar{N}_H \rangle & 0 & \lambda_5 \lambda_6 \langle \bar{N}_H \rangle \\ \lambda_3 \langle N_H^c \rangle & \lambda_3 \lambda_4 \langle N_H^c \rangle & 0 & \lambda_5 \lambda_6 \langle \bar{N}_H \rangle & M_\chi \end{pmatrix}.$$

The determinant is:

$$\det[M_{\text{singlets}}] = (M_{SX}^{11} M_{SX}^{22} - (M_{SX}^{12})^2)(\langle N_H^c \rangle)^2 (\langle \bar{N}_H \rangle)^2 \sim M_{\text{GUT}}^2 M_{23}^4.$$

Thus, there are two SM singlets (major components from S_Φ and $S_{\Phi'}$) with masses around the GUT scale, and four SM singlets with masses around M_{23}. These SM singlets do not contribute to RGE running below M_{23}.

3. **SM doublet mixings**: After flipped SU(5) gauge symmetry breaking, we have mass terms for SM doublets H_u, H_d, L_Σ, $\bar{L}_\Sigma$, L_χ, and $\bar{L}_\chi$:

$$W \supset -4\lambda_3 V_\Phi L_\Sigma \bar{L}_\chi - 4\lambda_5 V_{\Phi'} L_\chi \bar{L}_\Sigma + 2\lambda_1 \langle N_H^c \rangle L_\Sigma H_u + 2\lambda_2 \langle \bar{N}_H \rangle H_d \bar{L}_\Sigma + \mu H_d H_u + M_\chi L_\chi \bar{L}_\chi.$$

The corresponding mass matrix for the basis $(H_d, L_\Sigma, L_\chi)^t$ versus $(H_u, \bar{L}_\Sigma, \bar{L}_\chi)$ is:

$$M_{\text{doublets}} = \begin{pmatrix} \mu & 2\lambda_2 \langle \bar{N}_H \rangle & 0 \\ 2\lambda_1 \langle N_H^c \rangle & 0 & -4\lambda_5 V_{\Phi'} \\ 0 & -4\lambda_3 V_\Phi & M_\chi \end{pmatrix}.$$

The determinant is:

$$\det[M_{\text{doublets}}] = -16\lambda_3 \lambda_5 \mu V_\Phi V_{\Phi'} - 4\lambda_1 \lambda_2 M_\chi \langle \bar{N}_H \rangle \langle N_H^c \rangle.$$

Note that $V_\Phi \sim V_{\Phi'} \sim M_{\text{GUT}}$ and $\langle N_H^c \rangle = \langle \bar{N}_H \rangle \sim M_{23}$. We obtain two pairs of vector-like particles (major components belonging to L_Σ, $\bar{L}_\chi$, and L_χ, $\bar{L}_\Sigma$) with vector-like masses around the GUT scale, and one pair of vector-like particles (major components belonging to H_d and H_u) whose vector-like mass M_{LD} is:

$$M_{LD} \simeq \frac{\det[M_{\text{doublets}}]}{16\lambda_3 \lambda_5 V_\Phi V_{\Phi'}} \sim -\mu - \frac{\lambda_1 \lambda_2 M_\chi M_{23}^2}{4\lambda_3 \lambda_5 M_{\text{GUT}}^2}.$$

Since we need one pair of Higgs doublets with mass around the TeV scale to break electroweak gauge symmetry, we obtain that μ should be around the TeV scale, and M_χ has an upper bound for a concrete model with gauge coupling unification. For example, with $M_{23} = 3.66 \times 10^{16}$ GeV and $M_{\rm GUT} = 4.8 \times 10^{18}$ GeV as in the first case in the next subsection for gauge coupling unification, we obtain $M_\chi \leq 1.72 \times 10^7$ GeV. Moreover, we emphasize that even if $\mu = 0$, we can generate the corresponding effective $\mu_{\rm eff}$ term for one pair of light Higgs doublets from the above discussions.

With fine-tuning, there are two ways to have one pair of light Higgs doublets and very large vector-like mass M_χ for χ_F and $\bar{\chi}_F$. One way is to fine-tune the two terms in Eq. (46) so that $\det[M_{\rm doublets}] \sim \mu_{\rm eff} M^2_{\rm GUT}$ where $\mu_{\rm eff} \sim 1$ TeV. The other way is to replace the term $M_\chi \chi\bar{\chi}$ in Eq. (23) with:

$$W \supset y_\chi \chi(\Phi - 3\lambda_4 S)\chi + y'_\chi \bar{\chi}(\Phi' - 3\lambda_6 S')\bar{\chi},$$

where y_χ and y'_χ are small Yukawa couplings. Note that:

$$\langle\Phi\rangle - 3\lambda_4\langle S\rangle = {\rm diag}(4,4,4,0,4,4,4,0,4,4,4,8,0,0,0,4)V_\Phi,$$
$$\langle\Phi'\rangle - 3\lambda_6\langle S'\rangle = {\rm diag}(4,4,4,0,4,4,4,0,4,4,4,8,0,0,0,4)V_{\Phi'}.$$

We have:

$$W \supset 4y_\chi V_\Phi(\chi_F\chi_F + 2\chi_l\chi_l) + 4y'_\chi V_{\Phi'}(\bar{\chi}_F\bar{\chi}_F + 2\bar{\chi}_l\bar{\chi}_l).$$

Thus, the two terms give vector-like masses to χ_F, $\bar{\chi}_F$, χ_l and $\bar{\chi}_l$, while they do not give vector-like mass to χ_f and $\bar{\chi}_f$. Then we do not have the last term $M_\chi L_\chi \bar{L}_\chi$ in Eq. (44), and the (3,3) entry in the mass matrix in Eq. (45) is zero, i.e., there is no M_χ entry. Therefore, the vector-like mass for χ_F and $\bar{\chi}_F$ can be any value below M_{23}. In concrete model building, we just need one term in Eq. (48).

B. Gauge Coupling Unification

We study gauge coupling unification. First, consider the masses for additional particles. As discussed above, there is one pair of vector-like particles (major components belonging to Q_χ and $\bar{Q}_\chi$) with vector-like mass around M_χ. Also, the particles D^c_χ and $\bar{D}_\chi$ have vector-like mass M_χ. For simplicity, we assume the corresponding vector-like masses for these particles are the same, denoted as M_V because in the fine-tuning case we may not have the $M_\chi\chi\bar{\chi}$ term in Eq. (23). We also assume masses for color triplets of h_{10}, H, $\bar{H}$, N^c_χ, and $\bar{N}_\chi$ are around the SU$(2)_L\times$ SU$(3)_C$ unification scale M_{23}, and masses for $\Sigma_{\bar{f}}$, $\Sigma_{\bar{l}}$, Σ_f, Σ_l, $\chi_{\bar{f}}$, $\chi_{\bar{l}}$, χ_f, χ_l, Φ, and Φ' are around the GUT scale $M_{\rm GUT}$. We denote the Z-boson mass as M_Z and the supersymmetry breaking scale as M_S. The mass scales are assumed to satisfy $M_Z \leq M_S \leq M_V \leq M_{23} \leq M_{\rm GUT}$.

For gauge coupling unification, we consider one-loop renormalization group equation (RGE) running for gauge couplings because two-loop effects only give minor corrections as long as the theory is perturbative. The generic one-loop RGEs are:

$$(4\pi)^2 \frac{dg_i}{dt} = b_i g_i^3,$$

where $t = \ln \mu$ with μ being the renormalization scale, $g_1^2 \equiv 5g_Y^2/3$, and g_Y, g_2, and g_3 are gauge couplings for $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$, respectively.

Gauge coupling unification for flipped SU(5) is realized by first unifying α_2 and α_3 at scale M_{23}, then the gauge couplings of SU(5) and $U(1)_X$ further unify at $M_{\rm GUT}$. From M_Z to M_S, the beta functions are $b_0 \equiv (b_1, b_2, b_3) = (41/10, -19/6, -7)$. From M_S to M_V, they are $b_I = (33/5, 1, -3)$. From M_V to the α_2 and α_3 unification scale M_{23}, they are $b_{II} = (36/5, 4, 0)$.

Unification of α_2 and α_3 at M_{23} gives:

$$\alpha_2^{-1}(M_Z) - \alpha_3^{-1}(M_Z) = \frac{b_{0,2} - b_{II,2}}{2\pi} \ln \frac{M_S}{M_Z} + \frac{b_{I,2} - b_{II,2}}{2\pi} \ln \frac{M_V}{M_S} + \frac{b_{II,2} - b_{II,3}}{2\pi} \ln \frac{M_{23}}{M_V},$$

which can be solved for M_{23}.

The coupling α_1' of $U(1)_X$ relates to α_1 and α_5 at M_{23} by:

$$\alpha_1'(M_{23}) = \frac{5}{8}\alpha_1(M_{23}) - \frac{3}{8}\alpha_5(M_{23}).$$

Above M_{23}, the beta functions for $U(1)_X$ and SU(5) are $b_{III} \equiv (b_1', b_5) = (8, -2)$.

In numerical calculations, we choose central values $\alpha_3(M_Z) = 0.1182 \pm 0.0027$ [**?**], and the fine-structure constant $\alpha_{\rm EM}$ and weak mixing angle θ_W at M_Z as [**?**]:

$$\alpha_{\rm EM}(M_Z) = 128.91 \pm 0.02, \quad \sin^2\theta_W(M_Z) = 0.23120 \pm 0.00015.$$

Because the top quark pole mass is 172.7 ± 2.9 GeV [**?**], we might need supersymmetry breaking scale around or above the TeV scale to generate sufficient mass for the lightest CP-even Higgs boson in the MSSM. So we assume $M_S = 10^3$ GeV.

With $M_V = 10^7$ GeV, we plot gauge coupling unification in [Figure 1: see original paper]. We obtain $M_{23} = 3.66 \times 10^{16}$ GeV and $M_{\rm GUT} = 4.8 \times 10^{18}$ GeV. Note that $M_{23}^2/M_{\rm GUT} < 10^3$ GeV, so we can have one pair of light Higgs doublets without fine-tuning.

Since the GUT scale is close to the Planck scale 1.2×10^{19} GeV, we may need to include one-loop supergravity contributions to RGE running. It is reasonable to assume that, similar to non-supersymmetric gravity theory [**?**], supergravity contributions to one-loop RGEs of gauge couplings are proportional to gauge couplings linearly with the same coefficients for all gauge couplings because gravitons and gravitinos do not carry gauge charge. Note that the $U(1)_X$ gauge coupling is only slightly smaller than SU(5) at scales near the GUT scale, so supergravity contributions will only slightly increase the GUT scale [**?**].

As discussed above, with fine-tuning we can have very large M_V. Assuming $M_S = 10^3$ GeV, we plot $M_{\rm GUT}$ versus M_V for M_V from 10^3 GeV to 10^{16} GeV in [Figure 2: see original paper]. Varying M_V does not change M_{23} because these vector-like particles contribute the same one-loop beta functions to $SU(2)_L$ and $SU(3)_C$. Generally, increasing M_V decreases the GUT scale. In addition to threshold corrections at the supersymmetry breaking scale from sparticle mass differences, a few percent threshold corrections exist at the GUT scale in concrete GUT models. So gauge coupling unification for M_V close to 10^6 GeV is still fine, although there exists less than one percent discrepancy between gauge couplings. We find that for $M_{\rm GUT}$ from 10^{17} GeV to 10^{18} GeV, the corresponding M_V scale is from 5.54×10^{13} GeV to 5.54×10^9 GeV. It is interesting to have $M_{\rm GUT}$ around the string scale from 10^{17} GeV to 10^{18} GeV.

High-scale supersymmetry breaking [**?**, **?**, **?**] is interesting due to the string landscape [**?**, **?**, **?**, **?**, **?**, **?**], where we may explain the cosmological constant problem and gauge hierarchy problem [**?**, **?**], and all problems related to low-energy supersymmetry are solved automatically if the supersymmetry breaking scale is above the PeV scale (10^{15} eV $\equiv 10^6$ GeV) [**?**, **?**]. Assuming $M_S = 10^6$ GeV and $M_V = 3 \times 10^8$ GeV, we plot gauge coupling unification in [Figure 3: see original paper]. We obtain $M_{23} = 4.88 \times 10^{16}$ GeV and $M_{\rm GUT} = 7.57 \times 10^{17}$ GeV. Note that $M_{23}^2/M_{\rm GUT} \sim 1.25 \times 10^6$ GeV, so we can have one pair of light Higgs doublets at the PeV scale without fine-tuning. By the way, the SM Higgs doublet with electroweak-scale mass is obtained by fine-tuning the mass matrix for scalar Higgs doublets.

Remarks

We briefly discuss the simplest SO(10) model with flipped SU(5) embedding, pointing out its major phenomenological difficulty. We also explain how to generate the small mass M_χ.

A. SO(10) Model with One Adjoint Higgs Field

We can embed flipped SU(5) models into an SO(10) model with only one adjoint Higgs field Φ. In the superpotential Eq. (23), we change $W(\Phi, \Phi')$ to $W(\Phi)$, and replace the $\lambda_5 \bar{\Sigma}(\Phi' + \lambda_6 S')\bar{\chi}$ term with:

$$W \supset \lambda_5 \bar{\Sigma}(\Phi + \lambda_6 S')\bar{\chi}.$$

The discussions for splitting five/one-plets and ten-plets in χ, Σ, $\bar{\Sigma}$ and $\bar{\chi}$ are the same as in Section III, except we replace Φ' by Φ and $V_{\Phi'}$ by V_Φ.

Let us concentrate on the problem. The mass matrix for the basis $(Q_\Phi, Q_\chi)^t$ versus $(\bar{Q}_\Phi, \bar{Q}_\chi)$ is:

$$M_{QQ}^{XY} = \begin{pmatrix} M_{XY}^{11} & \lambda_3 \langle N_H^c \rangle \\ \lambda_5 \langle \bar{N}_H \rangle & M_\chi \end{pmatrix}.$$

The determinant is:

$$\det[M_{QQ}^{XY}] = M_{XY}^{11} M_\chi - \lambda_3 \lambda_5 \langle \bar{N}_H \rangle \langle N_H^c \rangle.$$

The discussions for the SM doublet mass matrix are the same as in Section IV.A, except we change $V_{\Phi'}$ to V_Φ in Eqs. (44) and (45). Without fine-tuning, M_χ still cannot be larger than about 10^8 GeV. Then:

$$\det[M_{QQ}^{XY}] \sim -\lambda_3 \lambda_5 \langle \bar{N}_H \rangle \langle N_H^c \rangle \sim -M_{23}^2.$$

Thus, there is one pair of vector-like particles (major components belonging to $Q_\Phi, \bar{Q}_\Phi$) with vector-like mass around the GUT scale, and one pair (major components belonging to $Q_\chi, \bar{Q}_\chi$) with vector-like mass around $M_{23}^2/M_{\rm GUT}$. Since χ_F and $\bar{\chi}_F$ have vector-like mass M_χ, we can easily show that gauge coupling unification cannot be realized. With large fine-tuning so that M_χ can be around $M_{23}^2/M_{\rm GUT}$ and $\det[M_{QQ}^{XY}] \sim 10^{-2} M_{23}^2$, we may achieve unification. With $M_\chi \leq 10^8$ GeV and without fine-tuning, we might also achieve gauge coupling unification by adding extra vector-like particles, for example, one or two pairs of **16** and $\bar{\mathbf{16}}$. However, these models are very complicated and still need some fine-tuning.

B. Explanation of the Suitable Mass M_χ

To have natural models, we need to explain why M_χ can be around 10^7 GeV. Two well-known ways to generate small masses are the Froggatt-Nielsen mechanism [**?**] and the see-saw mechanism [**?**]. Since we will try to generate SM fermion masses and mixings, and the suitable mass M_χ via the Froggatt-Nielsen mechanism by introducing extra flavor symmetry in future work, we employ the see-saw mechanism here.

An elegant solution to the strong CP problem is the Peccei-Quinn mechanism [**?**], which introduces a global axial symmetry $\mathrm{U}(1)_{PQ}$ broken spontaneously at some high energy scale. The original Weinberg-Wilczek axion [**?**, **?**] is excluded by experiment, particularly by non-observation of rare decay $K \to \pi + a$ [**?**]. Two viable "invisible" axion models evade experimental bounds: (1) the Kim-Shifman-Vainshtein-Zakharov (KSVZ) axion model, introducing a SM singlet $S_{\rm PQ}$ and extra vector-like quarks carrying $\mathrm{U}(1)_{PQ}$ charges while SM fermions and Higgs fields are neutral [**?**, **?**]; (2) the Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) axion model, introducing a SM singlet $S_{\rm PQ}$ and one pair of Higgs doublets, with SM fermions and Higgs fields also charged under $\mathrm{U}(1)_{PQ}$ [**?**, **?**]. From laboratory, astrophysical, and cosmological constraints, the $\mathrm{U}(1)_{PQ}$ symmetry breaking scale is limited to 10^{10} GeV to 10^{12} GeV [**?**]. Then the VEV of $S_{\rm PQ}$ is also roughly in this range. Interestingly, $\langle S_{\rm PQ} \rangle^2/M_{23}$ can be from 10^4 GeV to 10^8 GeV, giving the needed mass scale for M_χ.

Let us introduce one pair of spinor **16** and $\bar{\mathbf{16}}$ representation vector-like particles χ' and $\bar{\chi}'$. In the superpotential Eq. (23), we can forbid the $M_\chi \chi \bar{\chi}$ term by

$\mathrm{U}(1)_{PQ}$ symmetry, and introduce:

$$W \supset M_{\chi'}\chi'\bar{\chi}' + \lambda_{\mathrm{PQ1}} S_{\mathrm{PQ}}\chi'\bar{\chi} + \lambda_{\mathrm{PQ2}} S_{\mathrm{PQ}}\chi\bar{\chi}',$$

where λ_{PQ1} and λ_{PQ2} are Yukawa couplings, and $M_{\chi'}$ is a mass parameter around M_{23} that can be generated via the Froggatt-Nielsen mechanism.

Focusing on mixings between light states $\chi_F, \bar{\chi}_F$ of $\chi, \bar{\chi}$ and superheavy states $\chi'_F, \bar{\chi}'_F$ of $\chi', \bar{\chi}'$, after $\mathrm{U}(1)_{PQ}$ symmetry breaking the mass matrix for basis $(\chi_F, \chi'_F)^t$ versus $(\bar{\chi}_F, \bar{\chi}'_F)$ is:

$$M_{\chi_F\chi'_F} = \begin{pmatrix} 0 & \lambda_{\mathrm{PQ2}}\langle S_{\mathrm{PQ}}\rangle \\ \lambda_{\mathrm{PQ1}}\langle S_{\mathrm{PQ}}\rangle & M_{\chi'} \end{pmatrix}.$$

Thus, there is one pair of vector-like particles (major components $\chi'_F, \bar{\chi}'_F$) with GUT-scale mass, and one pair (major components $\chi_F, \bar{\chi}_F$) with vector-like mass:

$$M^{\chi_F}_{\mathrm{light}} \sim \frac{\lambda_{\mathrm{PQ1}}\lambda_{\mathrm{PQ2}}\langle S_{\mathrm{PQ}}\rangle^2}{M_{\chi'}} \sim 10^{4-8}\ \mathrm{GeV}.$$

Integrating out χ' and $\bar{\chi}'$ yields the high-dimensional operator:

$$W \supset -\frac{\lambda_{\mathrm{PQ1}}\lambda_{\mathrm{PQ2}}}{M_{\chi'}} S_{\mathrm{PQ}} S_{\mathrm{PQ}}\chi\bar{\chi},$$

which can generate the suitable vector-like mass M_χ. Thus, we can naturally generate light M_χ.

Discussion and Conclusions

We have embedded flipped SU(5) models into SO(10) models. After SO(10) gauge symmetry is broken down to flipped SU(5) gauge symmetry, we split the five/one-plets and ten-plets in $\chi, \Sigma, \bar{\Sigma}$ and $\bar{\chi}$ via the stable sliding singlet mechanism. Similar to flipped SU(5) models, gauge symmetry can be broken down to SM gauge symmetry by giving VEVs to singlet components of H and $\bar{H}$. The doublet-triplet splitting problem is solved naturally by the missing partner mechanism, and Higgsino-exchange mediated proton decay is elegantly avoided. Moreover, we showed that one pair of light Higgs doublets with major components from H_u and H_d exists for electroweak gauge symmetry breaking. Because two pairs of vector-like fields with similar intermediate-scale masses exist (major components from $Q_\chi, \bar{Q}_\chi$, and $D^c_\chi, \bar{D}_\chi$), we can achieve $\mathrm{SU}(5) \times \mathrm{U}(1)_X$ gauge coupling unification at the GUT scale, which is reasonably (about one or two orders) higher than the $\mathrm{SU}(2)_L \times \mathrm{SU}(3)_C$ unification scale. In short, we keep the beautiful features and eliminate the drawbacks of flipped SU(5) models in our SO(10) models.

Furthermore, we briefly studied the simplest SO(10) model with flipped SU(5) embedding, finding that it cannot work without fine-tuning. We also explained how to generate the suitable vector-like mass M_χ for χ and $\bar{\chi}$.

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Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.