

Flavor violating Z' from $SO(10)$ SUSY GUT in High-Scale SUSY

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We propose an $SO(10)$ supersymmetric grand unified theory (SUSY GUT), where the $SO(10)$ gauge symmetry breaks down to $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$ at the GUT scale and $U(1)_X$ is radiatively broken at the SUSY-breaking scale. In order to achieve the observed Higgs mass around 126 GeV and also to satisfy constraints on flavor- and CP-violating processes, we assume that the SUSY-breaking scale is $O(100)$ TeV, so that the $U(1)_X$ breaking scale is also $O(100)$ TeV. One big issue in the $SO(10)$ GUTs is how to realize realistic Yukawa couplings. In our model, not only **16**-dimensional but also **10**-dimensional matter fields are introduced to predict the observed fermion masses and mixings. The Standard-Model quarks and leptons are linear combinations of the **16**- and **10**-dimensional fields, so that the $U(1)_X$ gauge interaction may be flavor-violating and such a flavor violating process is a promising signal to prove our model. We investigate the current constraints on the flavor-violating Z' interaction from the flavor physics and discuss prospects for future experiments.

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In this letter, we propose an $SO(10)$ supersymmetric Grand Unified theory (SUSY GUT), where the realistic fermion masses and mixings are achieved by introducing extra **10**-dimensional matter fields, based on Ref. [1]. In the minimal $SO(10)$ GUT, the SM quarks and leptons are embedded into three **16**-dimensional fields [2]. In this case, the mass spectrum of the SM fermions are inconsistent with the experimental result, because of the matter unification. In our model, the SM quarks and leptons come from **10**- and **16**-dimensional fields, and especially, the right-handed down-type quarks and left-handed leptons in the SM are given by the linear combinations of **10**- and **16**-dimensional fields. We assume that $SO(10)$ gauge symmetry breaks down to $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$ ($\equiv G_{SM} \times U(1)_X$) around 10^{16} GeV according to the nonzero vacuum expectation values (VEVs) of $SO(10)$ adjoint fields. Thus, the low-energy effective theory is an $U(1)_X$ extension of the SUSY SM with extra matters. The additional gauge symmetry will survive up to the SUSY scale, but we could expect that it is radiatively broken, as the electroweak (EW) symmetry breaking in the minimal supersymmetry Standard Model (MSSM). We assume that SUSY particles in the SUSY SM, except for gauginos, reside around 100 TeV, in order to realize the observed 126 GeV Higgs mass and also to satisfy constraints on flavor- and/or CP-violating processes. The gauge coupling unification is rather improved when only the gaugino masses are around 1 TeV [3], and the dangerous dimension-five proton decay is suppressed [4]. On the other hand, since $\tan\beta$ (the ratio of the VEVs of the two Higgs doublets in the SUSY SM) is close to one, it is difficult to explain the large hierarchy between top and bottom quarks when all the matter fields are embedded into only **16** representational representations. In our model, the introduction of **10**-representational matter fields makes it possible to explain the large hierarchy. In the high-scale SUSY, the UV theory of the SM need not be the MSSM. The $U(1)_X$ extension of the SUSY SM with extra matters is an alternative model, motivated by the $SO(10)$ SUSY GUTs.

The mass of the Z' boson associated with the gauged $U(1)_X$ may be $O(100)$ TeV corresponding to the SUSY scale, so that it may be viable in the searches for flavor violations. The right-handed down-type quarks and left-handed leptons in the SM are given by linear combinations of the parts of **10**- and **16**-dimensional fields. Thus, that generically leads to flavor-violating Z' interaction and crucial promises against flavor experiments. We will see that tree-level Flavor Changing Neutral Currents (FCNC) induced by the Z' boson are generated and they largely contribute to the flavor violation processes: for instance, $\mu \rightarrow 3e$, μ - e conversion in nuclei, and $K^0 - \bar{K}^0$ and $B_{d/s}^0 - \bar{B}_{d/s}^0$ mixings. Especially, we find that the μ - e conversion and the CP-violation in K system provide the strongest constraints with our model.

1. Setup of $SO(10)$ SUSY GUT

We introduce a **10**-dimensional matter field in the each generation in addition to **16**-dimensional matter fields. Three $SO(10)$ -singlet matter fields S_i are also added to achieve the realistic masses of neutrinos [1]. The matter fields $\mathbf{10}_i$ and $\mathbf{16}_i$ are decomposed as in Table 1. For convenience, the assignment of $SU(5) \times U(1)_X$ is also shown in Table 1. The superpotential is written down according to the $SO(10)$ gauge symmetry introducing $\mathbf{10}_H$, $\mathbf{16}_H$ and $\overline{\mathbf{16}}_H$ Higgs fields to break the

	Q_L	U_R^c	E_R^c	\hat{L}_L	\hat{D}_R^c	N_R^c
$SO(10)$	16					
$SU(5) \times U(1)_X$	$(\mathbf{10}, -1)$			$(\bar{\mathbf{5}}, 3)$		$(\mathbf{1}, -5)$
G_{SM}	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$	$(\mathbf{1}, \mathbf{1}, 1)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	$(\mathbf{1}, \mathbf{1}, 0)$
	L'_L	D'_R^c	\bar{L}'_L			
$SO(10)$	10					
$SU(5) \times U(1)_X$	$(\bar{\mathbf{5}}, -2)$			$(\mathbf{5}, 2)$		
G_{SM}	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$		

Table 1: Charge assignment for matter fields. Charge assignment for G_{SM} is denoted as $(SU(3)_c, SU(2)_L, U(1)_Y)$. $U(1)_X$ gauge coupling constant is normalized as $g_X = g/\sqrt{40}$ at GUT scale, where g is $SO(10)$ gauge coupling constant.

EW and $U(1)_X$ gauge symmetries:

$$W_Y = h_{ij} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H + f_{ij} \mathbf{16}_i \bar{\mathbf{16}}_H S_j + g_{ij} \mathbf{10}_i \mathbf{16}_j \mathbf{16}_H \\ + \mu_{BL} \mathbf{16}_H \bar{\mathbf{16}}_H + \mu_H \mathbf{10}_H \mathbf{10}_H + \mu_{10ij} \mathbf{10}_i \mathbf{10}_j + \mu_{Sij} S_i S_j. \quad (1.1)$$

We assume that the mass parameters μ_{BL} , μ_{10} and μ_H are around SUSY scale (m_{SUSY}) and μ_S is much smaller to realize the tiny neutrino masses. In addition, two $SO(10)$ adjoint Higgs fields, $\mathbf{45}_H$ and $\mathbf{45}'_H$, are introduced in our model. They develop nonzero VEVs, and then the $SO(10)$ gauge symmetry breaks down to $G_{SM} \times U(1)_X$ at the GUT scale. The low-energy effective theory is the $U(1)_X$ extension of the SUSY SM with $\mathbf{10}$ - and $\mathbf{16}$ -dimensional matter fields. The superpotential in the $U(1)_X$ extension of the SUSY SM is shown in Ref. [1].

After the $U(1)_X$ symmetry breaking, the chiral superfields \hat{D}_{Ri}^c and D'_{Ri}^c (\hat{L}_{Li} and L'_{Li}) mix each other, and we find the massless modes which correspond to the SM right-handed down-type quarks and left-handed leptons. Eventually, the relevant Yukawa couplings for quarks and charged leptons are described as

$$W_Y^{SSM} = h_{uij} Q_{Li} U_{Rj}^c H_u + Y_{dij} Q_{Li} D_{Rj}^c H_d + Y_{eij} L_{Li} E_{Rj}^c H_d + \tilde{\mu}_{ij} (\bar{D}_{Rhi}^c D_{Rhj}^c + \bar{L}_{Lhi} L_{Lhj}). \quad (1.2)$$

D_{Ri}^c and L_{Li} (D_{Rhi}^c and L_{Lhi}) are the (heavy) chiral superfields of right-handed down-type quarks and left-handed leptons in the mass bases. Note that the hierarchy between top and bottom is realized by the mixing and the effective Yukawa coupling constants for the SM down-type quarks and charged leptons are described as

$$(Y_d)_{ij} = (h_{uik} + \varepsilon_{dik}) (\hat{U}_{D_R^c})_{kj}, \quad (Y_e)_{ij} = (\hat{U}_{L_L}^T)_{ik} (h_{ukj} + \varepsilon_{ekj}). \quad (1.3)$$

$(\hat{U}_{D_R^c})_{kj}$ and $(\hat{U}_{L_L})_{ik}$ are the mixing parameters between $\mathbf{10}$ - and $\mathbf{16}$ -dimensional matter fields, and the additional parameters, $\varepsilon_{d,ekj}$, are originated from the higher dimensional parameters. Then, the realistic Yukawa couplings are achieved.

The SM right-handed down-type quarks and left-handed leptons are given by the linear combinations of quarks and leptons in $\mathbf{10}$ - and $\mathbf{16}$ -dimensional matter fields, respectively. Since the fields in $\mathbf{10}$ and $\mathbf{16}$ representations carry different $U(1)_X$ charges, the SM fields have flavor-dependent

$U(1)_X$ interaction. The $U(1)_X$ gauge interactions of right-handed down-type quarks and left-handed leptons are described in the interaction basis as $\mathcal{L}_g = -ig_X(3\bar{\hat{\phi}}_i Z' \hat{\phi}_i - 2\bar{\psi}'_i Z' \psi'_i)$, where the factors 3 and -2 are $U(1)_X$ charges for the fermionic components $\hat{\phi}_i$ and ψ'_i of the chiral superfields $\hat{\psi}_i$ and ψ'_i .¹ Z' is the $U(1)_X$ gauge boson and g_X is defined as $g_X = g/\sqrt{40}$ at GUT scale, where g is the $SO(10)$ gauge coupling constant. Using the unitary matrix U_ψ , we define the flavor-violating couplings A_{ij}^φ for the SM fermions as $\mathcal{L}_g = -ig_X \bar{\varphi}_i (5(\hat{U}_\psi^\dagger \hat{U}_\psi)_{ij} - 2\delta_{ij}) Z' \varphi_j \equiv -ig_X A_{ij}^\varphi \bar{\varphi}_i Z' \varphi_j$, where φ is the fermion component of the chiral superfield ψ in the mass base and denotes right-handed down-type quark (d_R^c) and left-handed lepton (l_L). The flavor violating couplings A_{ij}^φ depend on the parameters, ε_d and ε_e . Note that at least $\varepsilon_1 \gtrsim O(10^{-5})$ is required to compensate for the small up quark mass, assuming $\varepsilon_{dij} = \varepsilon_i \delta_{ij}$. As discussed in Ref. [1], we find that all elements of the flavor violating couplings are $O(1)$, so that we need careful analyses of their contributions to flavor physics, even if the Z' boson is quite heavy.

2. Flavor physics

The large tree-level FCNCs involving the Z' boson are promised in our model. Here, we sketch the relevant constraints on the flavor-violating Z' interactions and give prospects for future experiments.

In our model, the SUSY SM Higgs doublets are charged under $U(1)_X$, so that their nonzero VEVs contribute to the Z' mass ($m_{Z'}$) as well as the SM gauge bosons. The mass mixing between Z and Z' is generated by the VEVs as well. Then the Z' interaction is described by the mixing and the tree-level FCNCs. The flavor-violating couplings significantly contribute to $B_{d/s}^0 - \bar{B}_{d/s}^0$ and $K^0 - \bar{K}^0$ mixings, flavor-violating decays, and μ - e conversion in nuclei. Below, we summarize the constraints relevant to the Z' interaction, and discuss the predictions in flavor physics.

The most relevant processes would be the $\mu \rightarrow 3e$ process and the μ - e conversion process in the lepton flavor violation. The current upper bound on the branching ratio of $\mu \rightarrow 3e$ is 1.0×10^{-12} [5]. We find that our model is safe for the current experimental bound as long as $m_{Z'}$ is $O(100)$ TeV [1]. We also evaluate the branching ratios of other lepton flavor violating decays, and we find that they are also much below the current experimental upper bounds. The flavor violating coupling A_{12}^{lL} also gives rise to the μ - e conversion process. In our model, the branching ratio for the Au target is close to the current upper bound at the SINDRUM-II [6]. The branching ratios for the other materials are estimated as $O(10^{-13})$ as well, so that we expect that our model could be proved in the future experiments.

The Z' FCNCs contribute to the mass splitting and CP violation in neutral meson systems. The measurement of $K^0 - \bar{K}^0$ oscillation is a strong probe on both real and imaginary part of $(A_{12}^{dR})^2$. Especially, the CP violation gives a sever constraint on the FCNC, so that the Z' mass has to be heavier than a few PeV, if A_{12}^{dR} possesses $O(1)$ CP phase. The detail analysis will appear in the future.

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¹In the $SU(5)$ description, $\hat{\psi}_i$ and ψ'_i can be embedded into $\bar{\mathbf{5}}$ -representational fields.

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