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Split Supersymmetry in an Orbifold GUT

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Abstract

We propose a supersymmetric $SU(5)$ orbifold GUT in 5 dimensions in which supersymmetry breaking at the boundaries give rise to split supersymmetry spectrum. The extra dimension is compactified on a $S^1/Z_2 \times Z_2'$ orbifold having two fixed points. The standard model fermions are localized in the standard model brane, where supersymmetry is broken by the nonvanishing of the F-term of a superfield X at some intermediate scale. All scalar superpartners acquires mass at this stage. The standard model gauginos and higgsinos remain light, since their masses are protected by R-symmetry and induced only by loop contributions and contact interaction in our brane. Usual features of orbifold GUTs are preserved in this scenario and proton decay and neutrino mass problems are solved.

Introduction: The simplest grand unified theory, which accomodates the standard model, is based on the gauge group $SU(5)$. Inspite of its simplicity, there are several problems in the simplest version. Many extensions were thus considered with varied consequences. To solve the gauge hierarchy problem, supersymmetry was introduced. But the supersymmetric models introduce more problems. Recently it has been suggested that if supersymmetry is broken at a very high scale, then many problems associated with low energy supersymmetry will disappear [1, 2]. These split supersymmetric models will have the standard model fermions at low energy but their superpartners will be heavy. Only the superpartners of the scalar and vector particles remain light, which can allow gauge coupling unification and solve dark matter problem. Although there are attempts to solve the hierarchy problem in split supersymmetric models [3], in most models of split supersymmetry [1, 2, 4] it was argued that since we have seen fine tuning in nature like the cosmological constant, we should not insist on solutions of fine tuning.

We study a specific scheme of supersymmetry breaking in an orbifold GUT which can give us the required spectrum of the superfields, and in addition, maintain all the nice features of orbifold GUTs [7, 8]. To explain the smallness of the neutrino masses we propose a distant breaking mechanism in orbifold GUTs in addition to the usual possibilities. The present supersymmetry breaking mechanism is similar to the original proposal of split supersymmetry using Scherk-Schwarz mechanism [9] in extra dimensions [1], while the distant breaking mechanism for neutrino mass is similar to that applied in models of extra dimensions [5, 6].

We start with a supersymmetric SU(5) orbifold GUT in 5 dimensions with two fixed points at $\mathcal{O}$ and $\mathcal{O}'$ [7, 8]. In one of the branes ($\mathcal{O}$) $SU(5)$ is unbroken, while at the other brane ($\mathcal{O}'$) only the standard model gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$ is present. We confine all the standard model fermions at the standard model brane $\mathcal{O}'$ [8]. Supersymmetry is broken at some intermeiate energy scale in the standard model brane ($\mathcal{O}'$)

when the F-term of a scalar field X acquires a nonvanishing value [1]. This makes all the scalar superfields as heavy as the supersymmetry breaking scale. However, the R-symmetry prevents the gauginos and higgsinos from acquiring any mass. Effective higher dimensional mass terms are allowed for the gauginos and higgsinos, which may be induced by gravitational effects or by anomaly [1], which are of the order of electroweak symmetry breaking scale. Since the fermions are confined in the standard model brane at $\mathcal{O}'$, fast proton decay are naturally prevented. The neutrino mass problem could be solved by introducing singlet right-handed neutrinos or triplet Higgs scalar in the standard model brane. We also propose a new possibility of distant breaking in orbifold GUTs to explain the smallness of the neutrino masses [6].

The model: Orbifold GUTs have been studied extensively for both SU(5) [7, 8] and SO(10) [10] grand unified groups. We consider a supersymmetric SU(5) orbifold GUT in 5 dimensions with N=1 supersymmetry. The 5D space-time is factorized to 4D Minkowski space M_4 (with coordinates x_μ, $\mu = 0, 1, 2, 3$) and the 5th dimension compactified on an orbifold $S^1/(Z_2 \times Z_2')$. The circle S^1 with radius R (with $R^{-1} \sim M_{GUT} = M_U$) will be mod out by a discrete Z_2 transformation with the equivalence relation $\mathcal{P}: \ y \to -y$, where $y = x_5$. We then divide S^1/Z_2 by the second Z_2' which acts as $\mathcal{P}': \ y' \to -y'$ with $y' = y + \pi R/2$. There are then two fixed points at the points $y = 0$ and $y = \pi R/2 \equiv \ell$, where there will be two 4-dimensional 3 branes $\mathcal{O}$ and $\mathcal{O}'$, respectively. The action of the two Z_2 and Z_2' parities $\mathcal{P}$ and $\mathcal{P}'$ on any generic field $\Phi(x_\mu, y)$ in the bulk will be defined by

$$\begin{aligned} \mathcal{P} &: \ \Phi(x_\mu, y) \to \Phi(x_\mu, -y) = P_\Phi \ \Phi(x_\mu, y) \\ \mathcal{P}' &: \ \Phi(x_\mu, y') \to \Phi(x_\mu, -y') = P'_\Phi \ \Phi(x_\mu, y'). \end{aligned} \tag{1}$$

The action of $\mathcal{P}$ and $\mathcal{P}'$ give eigenvalues ± 1. The fields $\Phi_{\pm\pm}(x_\mu, y)$ with eigenvalues $\{\mathcal{P}, \mathcal{P}'\} \equiv \{\pm, \pm\}$ will then have the following mode expansion

$$\Phi_{++}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \sum_{n=0}^{\infty} \Phi_{++}^{(2n)}(x_\mu) \cos \frac{2ny}{R},$$

$$
\begin{aligned}
\Phi_{+-}(x_\mu, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=0}^{\infty} \Phi_{+-}^{(2n+1)}(x_\mu) \cos\frac{(2n+1)y}{R}, \\
\Phi_{-+}(x_\mu, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=0}^{\infty} \Phi_{-+}^{(2n+1)}(x_\mu) \cos\frac{(2n+1)y}{R}, \\
\Phi_{--}(x_\mu, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=0}^{\infty} \Phi_{--}^{(2n+2)}(x_\mu) \cos\frac{(2n+2)y}{R},
\end{aligned} \tag{2}
$$

and hence only the 4D Kaluza-Klein field with eigenvalues $++$ can have massless zero mode. The fields Φ_{++} and Φ_{+-} can be non-vanishing at the brane $\mathcal{O}$ at $y = 0$, while the fields Φ_{++} and Φ_{-+} can be non-vanishing at the brane $\mathcal{O}'$ at $y = \ell$.

In 5D the local Lorentz group is O(5). The Weyl projection operator γ_5 is part of O(5) and hence both the left-chiral and right-chiral fields of 4D belong to the same representation of any 5D field. The $N = 1$ supersymmetry in 5D will thus contain 8 real supercharges, which in 4D will imply an $N = 2$ supersymmetry. For any realistic orbifold grand unified theory, the parity assignment corresponding to the discrete symmetries $\mathcal{P}$ and $\mathcal{P}'$ should reduce $N = 2$ supersymmetry to $N = 1$ supersymmetry in 4D and also break the $SU(5)$ symmetry to the standard model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. This can be achieved by the parity assignments,

$$
\mathcal{P} = \text{diag}\,\{+1, +1, +1, +1, +1\} \quad \text{and} \quad \mathcal{P}' = \text{diag}\,\{-1, -1, -1, +1, +1\}. \tag{3}
$$

where these matrix representations of $\mathcal{P}$ and $\mathcal{P}'$ acts on the fundamental representation of $SU(5)$. Thus all $SU(5)$ components of any multiplet will have the same parity under $\mathcal{P}$, while the components of the $SU(5)$ multiplets that are invariant under the standard model $SU(3)_c \times SU(2)_L \times U(1)_Y$ (denoted by the index a) will have opposite parity compared to the fields belonging to the coset space $SU(5)/SU(3)_c \times SU(2)_L \times U(1)_Y$ (denoted by the index $\hat{a}$) under $\mathcal{P}'$.

The vector multiplet of $N = 2$ supersymmetry contains a vector supermultiplet V_a and a scalar supermultiplet Σ_a of $N = 1$ supersymmetry. The parity assignments are inputs in orbifold GUTs, which determine the matter contents. One convenient choice for the parity operator $\mathcal{P}$ is even for the vector multiplets and odd for the scalar multiplets. The $(\mathcal{P}, \mathcal{P}')$ assignments for the vector and scalar multiplets are then given by,

$$V^a \equiv (+,+); \quad V^{\hat{a}} \equiv (+,-); \quad \Sigma^{\hat{a}} \equiv (-,+); \quad \Sigma^a \equiv (-,-).$$

Thus, only V^a will have zero modes in the bulk. Both the fields V^a and $V^{\hat{a}}$ will exist in the brane $\mathcal{O}$ at $y = 0$ and hence all fields will experience complete $SU(5)$ invariance. In the brane $\mathcal{O}'$ at $y = \ell$ the fields V^a and $\Sigma^{\hat{a}}$ will be present and all other fields will experience only the standard model gauge symmetry in this brane. Thus $SU(5)$ symmetry will be broken to the standard model in both the bulk and also the brane at $\mathcal{O}'$.

In the present scenario we shall assume that the standard model particles are localized at the $\mathcal{O}'$ brane at $y = \ell$, where $SU(5)$ is broken to the standard model. This is highly convenient for several reasons as pointed out in [8]. The quarks and the lepton multiplets are just the one required by the standard model: $q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, u_L^c, d_L^c, $\ell_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ and e_L^c, which remain massless in this brane. Supersymmetry is now broken at a very high scale and the superpartners squarks and sleptons become heavy, although the higgsinos and the gauginos remain light.

We shall now discuss the supersymmetry breaking mechanism in this model, which can lead to the split supersymmetry particle spectrum. Supersymmetry is broken in the SU(5) invariant brane at $\mathcal{O}$ by the Scherk-Schwarz mechanism [9] or by the F-component of a radion chiral superfield $T = r + \theta^2$ [11]. We follow the same procedure as that of [1, 12]. This supersymmetry breaking background makes the minimum of the potential negative. The vacuum energy can then be made to vanish by fine tuning the supersymmetry breaking F-component of a chiral superfield X in the standard model brane $\mathcal{O}'$. This field couples directly to the standard model particles and hence makes all the scalar superpartners as heavy as the supersymmetry breaking scale. However, the gauginos and the higgsinos receive only anomaly mediated masses, which are of the order of electroweak symmetry breaking scale.

We add a constant superpotential

$$W = cM_5^3,$$

localized in the SU(5) invariant brane at $\mathcal{O}$ and break supersymmetry by the F-component of a radion chiral superfield $T = r + \theta^2$ [11], which appears in the Kähler potential

$$K = M_5^3(T + T^\dagger).$$

The tree-level effective Lagrangian for T and the conformal compensator $\phi = 1 + \theta^2 F_\phi$ is then given by

$$L = \int d^4\phi^\dagger\phi\theta K + \int d^2\theta\phi^3 W + h.c. \tag{4}$$

The corresponding scalar potential

$$V = M_5^3 \left(r|F_\phi|^2 + F_T^* F_\phi + 3cF_\phi + h.c \right) \tag{5}$$

can be minimized to get the supersymmetry breaking condition

$$F_\phi = 0 \quad \text{and} \quad F_T = -3c,$$

with vanishing tree-level potential. The gravitino eats up the fermionic partner of T and becomes massive with mass $m_{3/2} = 1/r$ (assuming $c = 1$).

Although F_ϕ vanishes at the tree-level, at the one-loop level it becomes nonvanishing

$$F_\phi \sim \frac{1}{16\pi^2}\frac{1}{M_5^3 r^4} \ll m_{3/2}$$

with a negative potential at the minima. To cancel the vacuum energy, we add a chiral superfield X at the standard model brane $\mathcal{O}'$, where all the standard model fermions are localized. We assign a charge 2 to the field X under the R-symmetry and write down the superpotential at $\mathcal{O}'$, given by

$$W = m^2 X = \frac{1}{4\pi r^2} X \tag{6}$$

and a Kähler potential, given by

$$K = X^\dagger X - \frac{(X^\dagger X)^2}{M_5^2} + \cdots. \tag{7}$$

The minimum of the potential then breaks supersymmetry with F_ϕ nonvanishing

$$|F_\phi|^2 = m^4 = \frac{1}{16\pi^2 r^4} \tag{8}$$

and a vanishing cosmological constant.

The Kähler potential and the superpotential results in a positive mass squared term for the scalar component of X to be $m_X^2 \sim m^4/M_5^2$; mass for the fermionic component of X to be $m_{\psi_X} \sim m^4/M_5^3$ and a *vev* for X to be $\langle X\rangle \sim m^2/M_5$. The effective operators

$$\int d^4\theta \frac{1}{M_5^2} X^\dagger X Q^\dagger Q$$

would then make all the scalar partners of the fermion superfields to be as heavy as the supersymmetry breaking scale,

$$m_S \sim \frac{|F_X|}{M_5} \sim \frac{M_5}{M_{Pl}^4}. \tag{9}$$

On the other hand, the leading effective operators contributing to the gaugino masses,

$$\int d^2\theta \frac{m^2 X}{M_5^3} WW \quad \text{and} \quad \int d^4\theta \frac{X^\dagger X}{M_5^3} WW,$$

implies gaugino masses to be of the order of

$$M_i \sim \frac{|F_X|^2}{M_5^3}.$$

The origin of such effective operators could be from the contact interactions on the standard model brane or could be induced by anomaly or gravitationally. For the Higgs scalars, we assign a vanishing R-charge to H_u and H_d to prevent terms like $M_5 H_u H_d$. This makes the leading order couplings suppressed like the effective gaugino mass term leading to $\mu B \sim |F_X|^2/M_5^3$ and $\mu \sim M_i$.

The fundamental scale in the orbifold GUT model is the grand unification scale, which is of the order of $M_5 \sim M_G \sim 3 \times 10^{13}$ GeV. We assume the usual flat space relationship $rm_5^3 = M_{Pl}^2$. This gives a gravitino mass of $m_{3/2} \sim 10^{13}$ GeV and the supersymmetry breaking scale of $m_S \sim 10^9$ GeV. All the scalar partners of the fermion superfields acquire masses of the order of m_S. The gauginos and the higgsinos remain as light as 100 GeV. This spectrum will then be able to allow gauge coupling unification and also a LSP dark matter candidate.

Since the fermions are now confined to the standard model brane, there are no $SU(3)_c$ triplet Higgs scalars at low energy. Fast proton decay problem is thus automatically solved in this scenario. The quark and lepton masses come from the usual Yukawa couplings

$$\mathcal{L}_Y = h_u \bar{q}_L u_R H_1 + h_d \bar{q}_L d_R H_2 + h_e \bar{l}_L e_R H_2 \tag{10}$$

in the standard model brane, where only the standard model fermions are present and only the standard model interactions are allowed. The smallness of the neutrino masses could have several origin in this scenario, which we shall now discuss.

The simplest possibility would be to introduce three right-handed neutrinos $N_i, i = 1,2,3$ with large Majorana masses so that the left-handed neutrinos receive usual see-saw mass [14]. The couplings of the right-handed neutrinos are

$$L_{ss} = M_i N_i N_i + h_{\alpha i} \ell_\alpha N_i \phi + h.c., \tag{11}$$

where ϕ is the usual Higgs doublet of the standard model. The Majorana mass of the physical left-handed neutrinos is then given by

$$m_\nu = h^\dagger M^{-1} h \langle \phi \rangle^2 .$$

For the left-handed neutrino mass m_ν to be in the observed range, the scale of Majorana mass of the right-handed neutrinos should be lower than the grand unification scale. The most natural scale for the right-handed neutrino mass in this scenario is the supersymmetry breaking scale of about 10^9 GeV.

Another possibility of explaining the small neutrino mass is to introduce an $SU(2)_L$ triplet Higgs scalar $\xi \equiv [1, 2, -2]$ under the standard model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ [15]. Right-handed neutrinos are not required to be present in this scenario. If all the couplings of ξ are allowed, then lepton number is explicitly broken by its interactions

$$L_{trip} = f_{\alpha\beta} \ell_\alpha \ell_\beta \xi + \mu \xi \phi \phi + M \xi \xi \tag{12}$$

where the mass of the triplet Higgs M and the trilinear coupling μ are of the same order of magnitude, which is the lepton number violating scale. The neutrino mass matrix then becomes

$$m_{\nu\alpha\beta} = f_{\alpha\beta} \ \mu \frac{\langle \phi \rangle^2}{M^2}.$$

In the present scenario this scale could be either the supersymmetry breaking scale of 10^9 GeV or even the gravitino mass scale of 10^{13} GeV, to explain the observed neutrino masses.

In this orbifold GUT it is also possible to implement the distant breaking mechanism of neutrino masses in higher dimensions [6]. This new possibility is similar to that implemented in models with large extra dimensions [13]. In this distant breaking mechanism for neutrino masses, we introduce a triplet Higgs scalar ξ in the standard model brane. Lepton number is broken in the $SU(5)$ invariant brane by the vacuum expectation value of a singlet field. Another bulk singlet field then couples to this fields and the "shined" value of the bulk singlet in our brane introduces a small lepton number violation. The "shined" value of the bulk singlet η in our brane ($\langle \eta \rangle$) is very small. The coupling of this bulk singlet in our brane

$$L_\eta = \kappa \int_{\mathcal{O}'} d^4x \xi(x) \phi(x) \phi(x) \eta(x, y = \ell)$$

will then introduce a very tiny lepton number violating trilinear interaction.

The neutrino mass is then given by

$$m_{\nu\alpha\beta} = f_{\alpha\beta}\kappa\langle\eta\rangle\frac{\langle\phi\rangle^2}{M^2}.$$

Since the “shined” value of the bulk singlet in our brane could be as small as of the order of eV, it is possible to have the neutrino masses as observed, even with the triplet Higgs scalars as light as few hundred GeV. This Higgs scalar may then be detected in the next generation accelerator experiments through its same sign dilepton signals. If such signals are seen, then from a measurement of the couplings of the triplet Higgs scalar with the leptons it will be possible to determine the elements of the neutrino mass matrix, except for an overall scale.

Summary: We proposed a simple supersymmetric 5-dimensional $SU(5)$ orbifold GUT with the 5th dimension compactified on $S^1/Z_2 \times Z_2$. There are two fixed points, in one of which SU(5) is broken to the standard model, while in the other SU(5) remains invariant. The standard model brane contains the usual fermions. Supsersymmetry is broken by the F-component of a radion chiral superfield in the SU(5) invariant brane, while a chiral superfield breaks R-symmetry and supersymmetry in the standard model brane. The scalar partners of the usual fermions then becomes as heavy as the supersymmtry breaking scale, although the gauginos and the higgsinos remain as light as the electroweak symmetry breaking scale. This can then allow gauge coupling unification and the lightest LSP could become the dark matter candidate. The SU(3) triplet scalar becomes automatically heavy and there is no fast proton decay problem. We also suggested few possibilities of making neutrinos superlight, including a new distant breaking mechanism.

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