Probing Symmetry-Breaking Pattern Using Sfermion Masses

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Abstract

We study the mass spectrum of superparticles within supersymmetric grand unified models. For gaugino masses, it is pointed out that the GUT-relation in the SU(5) model is applicable to a more general case where a grand-unified gauge group breaks down to the standard model gauge group by several steps. We also show that the mass spectrum of squarks and sleptons carries the information on the breaking pattern of the gauge symmetry. It is demonstrated in some SO(10) models how the scalar mass spectrum distinguishes various SO(10) breaking patterns from each other.

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The Grand Unified Theory (GUT) has been attractive as a promising framework to explain the law of nature since its proposal \[1\]. The huge difference between the GUT scale and the weak scale gives rise to the famous gauge hierarchy problem. The prime motivation of introducing supersymmetry (SUSY) in a GUT \[2\] is that it will give a partial solution to this problem: SUSY can stabilize the hierarchy between the GUT scale and the weak scale against radiative corrections \[3\].

This wonderful theoretical framework, the SUSY-GUT, is consistent with the precise measurement of the weak-scale gauge coupling constants at LEP \[4\] for the minimal particle content of SUSY standard model \[5\]. Furthermore, the present non-observation of the nucleon decay is shown to be still consistent with the minimal version of the SUSY-GUT \[6\]. It is, however, not clear from the LEP data alone whether the minimal version of the SUSY-GUT is the whole story. For example, the solar neutrino experiments \[7\] suggest the neutrino oscillation à la Mikheyev–Smirnov–Wolfenstein \[8\], and it is naturally incorporated into the SO(10) grand unification with seesaw mechanism \[9\]. While the direct breaking of the SO(10) group into the standard model group \(G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y\) is obviously consistent with the LEP data, there are possibilities that there is an intermediate scale with chain symmetry breaking.\[10\]

An important virtue of the SUSY-models is that the soft SUSY-breaking mass parameters can be novel probes of physics at very high energies. In this letter we point out that the gaugino mass spectrum generally satisfies the GUT-relation as far as the standard model gauge group is embedded into a simple group, irrespective of the symmetry breaking pattern. On the other hand, the squark and slepton mass spectrum will be shown to carry the information on the breaking pattern of the gauge symmetry. Therefore, the gaugino and the scalar mass spectrum will play a complementary role to select among the models of SUSY-GUT experimentally. We will demonstrate how the scalar mass spectrum distinguishes various SO(10) breaking patterns from each other.

We first consider the gaugino mass spectrum. We expect that the gaugino mass parameters are common at the unification scale \(M_U\). Though it is known that the vacuum expectation values of the fields responsible for the GUT symmetry breaking would give a non-universal contribution to the gaugino

*An explicit example was first given in Ref. \[15\] from different motivation.
masses \[10\], it is suppressed by powers of \(M_U/M_{\text{Planck}}\), which can be neglected as far as the unification scale is not very close to the Planck scale. Then we can show that the spectrum of the gaugino masses always satisfies the so-called GUT-relation \[11\]

\[
\frac{M_1(m_Z)}{\alpha_1(m_Z)} = \frac{M_2(m_Z)}{\alpha_2(m_Z)} = \frac{M_3(m_Z)}{\alpha_3(m_Z)} = \frac{M_{\text{GUT}}(M_U)}{\alpha_{\text{GUT}}(M_U)},
\]

irrespective of the breaking pattern if the gauge group is unified in a simple group at a high mass scale \(M_U\). Though one can prove \([11]\) in a general framework, we will demonstrate here that the GUT-relation indeed holds in some breaking patterns of \(SO(10)\) group, namely the direct breaking into the standard model gauge group ("direct breaking"),

\[
SO(10) \xrightarrow{M_U} G_{\text{SM}},
\]

"Pati-Salam",

\[
SO(10) \xrightarrow{M_U} SU(4)_{PS} \times SU(2)_L \times SU(2)_R \xrightarrow{M_{PS}} G_{\text{SM}},
\]

and "3221" \[13]\]

\[
SO(10) \xrightarrow{M_U} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{B-L}} G_{\text{SM}}.
\]

We assume the particle content of the Minimal Supersymmetric Standard Model (MSSM) below the breaking scales, \(M_U, M_{PS}\) or \(M_{B-L}\), for each breaking patterns respectively. These breaking scales are supposed to be much higher than the SUSY-breaking scale.

It is obvious that the GUT-relation of the gaugino masses holds in the "direct" breaking. For the "Pati-Salam" case, the \(SU(3)_C\) gaugino comes solely

\[\text{1}\]We define \(\alpha_2 = \alpha/\sin^2 \theta_W\) and \(\alpha_1 = \frac{5}{3}\alpha/\cos^2 \theta_W\) throughout the paper. The symbols \(M_i\) stand for gaugino masses of various gauge groups, \(g_i\) the gauge coupling constants, and \(\alpha_i = g_i^2/4\pi\). The GUT-relation is a consequence of the one-loop renormalization group equations. The GUT-relation fails to hold at the two-loop level \([12]\), but numerically the effect is small \([13]\). The threshold effects are also neglected since the threshold corrections on the gaugino masses at the GUT-scale can be almost absorbed in the threshold corrections on the gauge coupling constants, so that there are no large logarithms appearing in the corrections to the GUT-relation of the gaugino masses \([14]\). The GUT-relation can be violated only at the order of \(\alpha/\pi\).
from $SU(4)_{PS}$ gaugino, and $SU(2)_L$ remains unbroken at the symmetry-breaking scale of the “Pati-Salam” symmetry ($M_{PS}$). Then the following equalities hold:

$$\frac{M_3(m_Z)}{\alpha_3(m_Z)} = \frac{M_4(M_{PS})}{\alpha_4(M_{PS})} = \frac{M_{10}(M_U)}{\alpha_{10}(M_U)} \quad (5)$$

for the $SU(3)C$ gaugino, and

$$\frac{M_2(m_Z)}{\alpha_2(m_Z)} = \frac{M_{2L}(M_{PS})}{\alpha_{2L}(M_{PS})} = \frac{M_{10}(M_U)}{\alpha_{10}(M_U)} \quad (6)$$

for the $SU(2)_L$ gaugino. Here, $M_{10}$ represents the $SO(10)$ gaugino mass. There is a complication for the $U(1)_Y$ gaugino because it is a mixture of $SU(2)_R$ and $SU(4)_{PS}$ gauginos. Since $\sqrt{3}Y = \sqrt{2}T_{15}^4 + \sqrt{3}T_{2R}^3$, the gauge coupling constants satisfy

$$\frac{1}{\alpha_1} = \frac{2}{5} \frac{1}{\alpha_4} + \frac{3}{5} \frac{1}{\alpha_{2R}} \quad (7)$$

at $M_{PS}$. On the other hand, the gauge fields $A^\mu$ mix as $g_1^{-1}A_1 = g_4^{-1} \sqrt{2}A_{15}^4 + g_{2R}^{-1} \sqrt{3}A_{2R}^3$, and the gaugino fields $\lambda$ mix correspondingly as

$$\frac{1}{g_1} \lambda_1 = \frac{1}{g_4} \sqrt{2} \lambda_{15}^4 + \frac{1}{g_{2R}} \sqrt{3} \lambda_{2R}^3, \quad (8)$$

as required from the supersymmetry. Thus the gaugino mass is given as

$$\frac{M_1(m_Z)}{\alpha_1(m_Z)} = \frac{M_1(M_{PS})}{\alpha_1(M_{PS})} = \frac{2}{5} \frac{M_4(M_{PS})}{\alpha_4(M_{PS})} + \frac{3}{5} \frac{M_{2R}(M_{PS})}{\alpha_{2R}(M_{PS})} = \frac{M_{10}(M_U)}{\alpha_{10}(M_U)} \quad (9)$$

where we used the solution to the renormalization group equations of $M_4$ and $M_{2R}$. Therefore from Eqs. (5,6,9), the gaugino masses $M_3$, $M_2$ and $M_1$ satisfy the GUT-relation \[\square\]. Exactly the same argument applies to the “3221” breaking pattern as well.

Summarizing the above discussion, we have demonstrated that the gaugino masses satisfy the GUT-relation even with an intermediate scale, irrespective of the breaking patterns, as far as the whole gauge groups are unified in $SO(10)$. More general treatment will be given elsewhere\[\square\].

\footnote{We adopt the notation $T_{15}^4 = \frac{1}{\sqrt{24}} \text{diag}(1,1,1,-3)$ and $T_{2R}^3 = \frac{1}{2} \text{diag}(1,-1)$.}

\footnote{Note that our proof of the GUT-relation does not depend on the particle content of the models.}
An immediate consequence of the above observation is the following. The measurement of the gaugino masses at the weak scale will give us a useful suggestion on whether the standard model gauge group $G_{SM}$ is embedded into a simple group or not, irrespective of the breaking pattern. Recall that the gaugino masses do not satisfy the GUT-relation (1) in general if the gauge group is not unified as in flipped $SU(5)$ model. However, one cannot distinguish between the models which have different breaking patterns but from the same unification group.

Now we discuss the renormalization group evolution of the squark and slepton masses in the three breaking patterns. The renormalization-group equations for the scalar masses are given by

$$\frac{d}{d\ln \mu} m_a^2(\mu) = -\frac{2}{\pi} \sum_i C_2(R_{ai}) \alpha_i(\mu) M_i(\mu)^2 + \frac{3}{10\pi} Y_a \alpha_1(\mu) S(\mu), \quad (10)$$

$$\frac{d}{d\ln \mu} S(\mu) = \frac{b_1}{2\pi} \alpha_1(\mu) S(\mu), \quad (11)$$

$$S = \sum_a Y_a n_a m_a^2$$

where $i$ represents the gauge group, $a$ the species of the scalar, $C_2(R_{ai})$ the second Casimir invariant of the gauge group $i$ for the species $a$, $Y_a$ the hypercharge, and $n_a$ the multiplicity of the species $a$. In Eq. (10) we have neglected the Yukawa coupling contribution. This approximation should be valid for the first- and the second-generation fields. It is straightforward to generalize our results to the third generation by considering the effects of Yukawa coupling contributions. The contribution from $S$ is usually ignored since it is absent under the assumption of the universal scalar mass. For the MSSM, it is

$$S = m_2^2 - m_1^2 + \sum_{\text{generations}} (m_q^2 - 2m_u^2 + m_e^2 - m_l^2 + m_d^2). \quad (13)$$

The coefficients of the beta function $b_i$ are defined by

$$\frac{d}{d\ln \mu} \alpha_i^{-1} = -\frac{b_i}{2\pi}. \quad (14)$$

We refer to the chiral multiplets as $q$ for left-handed quark, $l$ left-handed lepton, $u$ right-handed up, $d$ right-handed down and $e$ for right-handed charged lepton. The tilde represents their scalar component. $m_q^2$ and $m_d^2$ stand for the soft SUSY breaking mass terms of the Higgs bosons with hypercharge $-1/2$ and $+1/2$, respectively.
Solving the renormalization-group equations we obtain

\[
m_a^2(\mu) = m_a^2(\mu_0) - \sum_i \frac{2}{b_i} C_2(R_i^a)(M_i^2(\mu) - M_i^2(\mu_0)) \\
+ \frac{3}{5b_1} Y_a(S(\mu) - S(\mu_0)),
\]

(15)

\[
S(\mu) = \frac{\alpha_1(\mu)}{\alpha_1(\mu_0)} S(\mu_0).
\]

(16)

Since the quantity \( S \) at the weak scale can be determined through measurements, we can easily take its contribution to the scalar masses into account. Therefore the appearance of \( S \) in the above equations does not prevent us from going further.

Let us examine how the sfermion mass spectrum at the breaking scale \( M_{SB} \) reflects the pattern of the gauge symmetry breaking. One may naively expect that scalars belonging to a single multiplet above \( M_{SB} \) have a common mass at \( M_{SB} \). There is, however, an important complication due to the presence of the so-called \( D \)-term contribution to the scalar masses which appears when the rank of the gauge group is reduced. In Refs. [16], it was demonstrated that the \( D \)-term contribution occurs when the gauge symmetry is broken at an intermediate scale due to the soft SUSY breaking terms. The existence of the \( D \)-term contribution in a more general situation was suggested in Ref. [17]. One can show a sizable \( D \)-term contribution generally exists once the soft SUSY breaking terms in the scalar potential are not universal [18]. Then we obtain the correction to the scalar mass terms of the form

\[
\sum_\alpha g_\alpha^2 \langle D^\alpha \rangle \phi^\dagger T^\alpha \phi.
\]

(17)

A \( D \)-term can be non-zero if the corresponding broken generator commutes with all unbroken generators. Such broken generators constitute a subgroup \( G' \). In particular, the \( D \)-term contribution arises when the rank of the group is reduced due to the gauge symmetry breaking. When \( SO(10) \)

\[\text{∥}\]

The assumption that the scalar masses have universal structure is a strong one. In fact, it is known that the non-universal soft SUSY breaking parameters emerge in the effective theory derived from superstring [3]. Even if they are universal at the Planck scale as in minimal supergravity or SUSY-breaking in dilaton \( F \)-term, the radiative corrections between the Planck and the symmetry breaking scale generally induce non-universality of the scalar masses.
breaks to $G_{SM}$, the rank is reduced by one and $G'$ is just $U(1)$. Thus the $D$-term contribution is expressed by one parameter $D$. This is also the case for chain breaking of $SO(10)$.

In the “direct” breaking, the scalar masses satisfy

$$m_{\tilde{q}}^2 = m_{16}^2 + g_{10}^2 D,$$
$$m_{\tilde{u}}^2 = m_{16}^2 + g_{10}^2 D,$$
$$m_{\tilde{e}}^2 = m_{16}^2 + g_{10}^2 D,$$
$$m_{\tilde{t}}^2 = m_{16}^2 - 3g_{10}^2 D,$$
$$m_{\tilde{d}}^2 = m_{16}^2 - 3g_{10}^2 D,$$

at the $SO(10)$ unification scale $M_U$. Since $M_U$ can be determined from the renormalization group equations of gauge coupling constants as well as the gaugino masses, the only free parameters are $m_{16}^2$ and $D$. Having five measurable scalar masses we can solve for $m_{16}^2$ and $D$, and still have three relations among them. A typical evolution of the scalar masses below $M_U$ is depicted in Fig. 1. It is clear that we can check whether the measured scalar masses are consistent with the “direct” breaking. Note that $S$ at the scale $M_U$ is

$$S(M_U) = m_2^2 - m_1^2.$$ (23)

If the two Higgs doublets belong to the same $10$ representation, the above equation becomes

$$S(M_U) = -4g_{10}^2 D.$$ (24)

In a more complicated model, we do not have predictability on $S$. However, the quantity $S$ can be measured at the weak scale, so that one can easily incorporate $S$ into analysis without knowing the physics at the GUT-scale. In Fig. 1, we took $S = 0$ for definiteness.

For the “Pati-Salam” case, we have four parameters: two independent scalar masses $m_L^2$ for the left-handed multiplet and $m_R^2$ for the right-handed multiplet below $M_U$, the parameter $D$, and the scale $M_{PS}$ itself. Thus we can solve for them from $m_{\tilde{g}}, m_{\tilde{l}}, m_{\tilde{a}}, m_{\tilde{d}}$ and $m_{\tilde{e}}$, and still have one relation

**The normalization and the sign of $D$ are arbitrary.

†† It is probably impossible to measure the SUSY-breaking part of the right-handed sneutrino mass as far as it has SUSY-invariant mass of the intermediate scale.
among them. The scalar masses satisfy
\begin{align*}
  m^2_{\tilde{q}} &= m^2_L + g_4^2 D, \quad (25) \\
  m^2_{\tilde{u}} &= m^2_R - (g_4^2 - 2g_{2R}^2) D, \quad (26) \\
  m^2_{\tilde{e}} &= m^2_R + (3g_4^2 - 2g_{2R}^2) D, \quad (27) \\
  m^2_{\tilde{t}} &= m^2_L - 3g_4^2 D, \quad (28) \\
  m^2_{\tilde{d}} &= m^2_R - (g_4^2 + 2g_{2R}^2) D, \quad (29)
\end{align*}

at $M_{PS}$. Recall that $g_4$ and $g_{2R}$ can be computed from the weak-scale coupling constants as a function of $M_{PS}$ alone. After eliminating $D$, $m^2_L$ and $m^2_R$, we obtain two relations,
\begin{align*}
  m^2_{\tilde{q}}(M_{PS}) - m^2_{\tilde{l}}(M_{PS}) &= m^2_{\tilde{u}}(M_{PS}) - m^2_{\tilde{d}}(M_{PS}), \quad (30) \\
  g_{2R}^2(M_{PS})(m^2_{\tilde{q}} - m^2_{\tilde{l}})(M_{PS}) &= g_4^2(M_{PS})(m^2_{\tilde{u}} - m^2_{\tilde{d}})(M_{PS}), \quad (31)
\end{align*}

and one of them should be used to determine $M_{PS}$. A typical evolution of the scalar masses is shown in Fig. 2. The Fig. 2(b) provides a magnified view around $M_{PS}$ so that the relations (30) and (31) are visible.

$S$ in the “Pati-Salam” case is
\[ S = m^2_2 - m^2_1 + 24(g_4^2 - g_{2R}^2) D \]

at $M_{PS}$. As in the case of the “direct” breaking, the value of $S$ depends on the Higgs structure. For the simplest case where the two Higgs doublets are in a single $(1, 2, 2)$, we have
\[ S = -4g_{2R}^2 D + 24(g_4^2 - g_{2R}^2) D. \]

In Fig. 2, we took $S = 0$ for definiteness as in the “direct” case.

The breaking pattern by “3221” has smaller symmetry below $M_U$ than the “Pati-Salam” case, and hence there are more parameters. Above the symmetry-breaking scale of $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ symmetry

\footnote{Here we have assumed the presence of two chiral superfields for each of the representations $(4, 1, 2)$, $(4^*, 1, 2)$, $(1, 1, 3)$ above $M_{PS}$ to achieve the unification of the gauge coupling constants at the unification scale $M_U$. The precise assignment of the quantum number is, however, irrelevant to our discussion since we can test the relations (30) and (31) without specifying the beta-function above $M_{PS}$.}
(\(M_{B-L}\)), there are four independent scalar masses \(m_{\tilde{q}L}^2\), \(m_{\tilde{q}R}^2\), \(m_{\tilde{l}L}^2\) and \(m_{\tilde{l}R}^2\) corresponding for left- and right-handed quark/lepton doublets. The scalar masses have the following contributions from the \(D\)-terms,

\[
\begin{align*}
m_{\tilde{q}}^2 &= m_{\tilde{q}L}^2 + g_{B-L}^2 D, \\
m_{\tilde{u}}^2 &= m_{\tilde{q}R}^2 - (g_{B-L}^2 - 2g_{2R}^2) D, \\
m_{\tilde{e}}^2 &= m_{\tilde{l}R}^2 + (3g_{B-L}^2 - 2g_{2R}^2) D, \\
m_{\tilde{l}}^2 &= m_{\tilde{l}L}^2 - 3g_{B-L}^2 D, \\
m_{\tilde{d}}^2 &= m_{\tilde{q}R}^2 - (g_{B-L}^2 + 2g_{2R}^2) D.
\end{align*}
\]

We have six unknown parameters \(m_{\tilde{q}L}, m_{\tilde{q}R}, m_{\tilde{l}L}, m_{\tilde{l}R}, M_{B-L}\) and \(D\), in contrast to the five observables. Therefore, we cannot solve for these parameters and neither check these relations. The scalar mass spectrum looks just disordered. A typical evolution is depicted in Fig. 3. Note that \(S\) in this case is rather complicated. In the figure, we have again took \(S = 0\) for definiteness.

In summary, we have shown that the gaugino masses and scalar masses carry complementary information on the symmetry breaking of the unification group. Assuming the universal gaugino masses at the GUT-scale, the gaugino masses satisfy the GUT-relation even with the chain breaking of the gauge symmetry, as far as the standard model gauge group \(SU(3)_C \times SU(2)_L \times U(1)_Y\) is embedded into a simple group. The breaking pattern is irrelevant. Therefore, the gaugino masses supply a unique tool to infer whether the standard model gauge group is unified in a simple group or not.

On the other hand, the scalar masses carry the information on the nearest symmetry breaking pattern above the weak-scale. For models with relatively large gauge group like \(SO(10)\) itself or Pati-Salam group \(SU(4)_{PS} \times SU(2)_L \times SU(2)_R\), we can solve for the original parameters of the model, and can also check whether the scalar mass spectrum is consistent with the model or not. It is remarkable that the relations are obtained without specifying the particle contents above the breaking scale. For models with relatively small gauge group, \(SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\), one may not be able to extract the original mass parameters. In any case, one can distinguish among the models by measuring the scalar masses.

*We have taken the same particle content as in Ref. [15], with a triplicate of representation \((1, 1, 2, -3/\sqrt{24})\) and its conjugate under \(SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\) symmetry.
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Figure Captions

Fig. 1 A typical evolution of the scalar masses under the “direct” breaking of $SO(10) \rightarrow G_{SM}$. $S$ in Eq. (12) is taken to be zero.

Fig. 2 A typical evolution of the scalar masses under the chain breaking $SO(10) \rightarrow SU(4)_{PS} \times SU(2)_L \times SU(2)_R \rightarrow G_{SM}$. The $D$-term contributions to the scalar masses are depicted in Fig. 2(b) so that the relations (30) and (31) are visible. $S$ in Eq. (12) is taken to be zero.

Fig. 3 A typical evolution of the scalar masses under the chain breaking $SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow G_{SM}$. The $D$-term contributions to the scalar masses are depicted in Fig. 3(b). $S$ in Eq. (12) is taken to be zero.
Fig. 1
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Fig. 2(a)
\[ m_{\text{scalar}}^2 [\text{GeV}^2] \]

**Fig. 2b**

- \( m_{\tilde{q}}^2 \)
- \( m_{\tilde{e}}^2 \)
- \( m_{\tilde{u}}^2 \)
- \( m_{\tilde{d}}^2 \)
- \( m_{\tilde{L}}^2 \)
- \( m_{\tilde{R}}^2 \)

\[ +g_4^2 D \]
\[ +\left(3g_4^2 - 2g_{2R}^2\right)D \]
\[ -(g_4^2 + 2g_{2R}^2)D \]
\[ -(g_4^2 - 2g_{2R}^2)D \]
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Fig. 3(a)
Fig. 3(b)
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