Supersymmetry breaking from somewhere in extra dimensions*

Tatsuo Kobayashi

Department of Physics, Kyoto University Kyoto 606-8502, Japan

Low-energy supersymmetry (SUSY) provides an attractive candidate for the fundamental theory beyond the Standard Model. However, SUSY must be broken due to the absence of experimental signatures below the weak scale. Various types of supersymmetry breaking and mediation mechanisms have been proposed. In recently proposed scenarios [2, 3] with extra dimensions, the SUSY breaking sector is spatially separated from the visible one literally. Another desirable property of a SUSY-breaking scenario is that the sparticle spectrum is distinctive of the scenario and detectable in future experiments. In this talk, we discuss a new mediation mechanism of SUSY breaking in the model with extra spatial dimensions. In our scenario, the modulus which does not directly couple to massless modes of the visible sector has a non-vanishing F-term, and moreover, characteristic spectra can be obtained depending on how to construct four-dimensional low-energy effective theories.

We consider four-dimensional effective theories with additional dimensions compactified at the scale M_c, which are smaller than the cutoff Λ of the effective theories. The compactification scale, i.e. the size of extra dimensions, is determined by the vacuum expectation value of a radius modulus T. We here assume that in the low-energy effective theories, the modulus superfield has an auxiliary vacuum expectation value, $\langle T\rangle = M_c + \theta^2 F_T$. We study the case that the contribution of the radius modulus dominates SUSY breaking. With other sources of SUSY breaking (nonzero F terms), there will exist additional effects on the soft SUSY breaking terms. When the Standard Model fields propagate in the bulk, the corresponding massive towers of Kaluza-Klein (KK) modes appear in the four-dimensional effective theories.

* This talk is based on the collaboration with K. Yoshioka [1].

The gauge kinetic term at μ is obtained

$$\int d\theta^2 S(\mu) W^\alpha W_\alpha + h.c., \tag{1}$$

where W^α is the field strength superfield and $S(\mu) = 1/(4g(\mu)^2)$.

A large number of KK modes contribute to β-functions of gauge couplings and anomalous dimensions. At $\mu > M_c$ the β-function of g is obtained [4]

$$\frac{d\alpha}{dt} = \frac{b_{KK}}{2\pi} N(\mu)\alpha^2 + \cdots \tag{2}$$

where $t = \ln\mu$, $\alpha = g^2/(4\pi^2)$ and b_{KK} is the beta-function coefficient determined by KK-mode contributions. We have neglected the ordinary logarithmic term. The energy-dependent constant N appears in summing up the leading-log contribution and indicates the number of KK states propagating in the loop diagrams. It is approximated by the volume of a sphere with radius Λ/μ, which is given by $N(\mu) \simeq \pi^{\delta/2}/\Gamma(1+\delta/2)(\Lambda/\mu)^\delta$ (δ is the number of extra dimensions).

The gaugino mass is extracted by replacing $M_C \to T$, that is, the gaugino mass appears from the auxiliary component of the T-dependent renormalized gauge coupling superfield. We obtain the soft mass of the gaugino zero-mode at the compactification scale,

$$M_g = -\frac{1}{2}\frac{\partial \ln S}{\partial \ln M_c}\frac{F_T}{M_c} = \frac{\beta}{2\alpha}\frac{F_T}{M_c} = b_{KK} N \frac{\alpha}{4\pi}\frac{F_T}{M_c} \tag{3}$$

where $N \equiv N(M_c)$. As is well-known, the ratio M_g/α is renormalization-group invariant and therefore eq. (3) still holds below the compactification scale. Similar to gauge mediation, M_g is proportional to the gauge beta-function coefficient of messenger fields. The formula (3) is also similar to the moduli-dominant SUSY breaking in superstring theory, where the gauge kinetic function has T-dependent threshold corrections due to KK modes [5]. In this case, the coefficient is written by the $N = 2$ sector and the Green-Schwarz coefficient due to the target-space duality anomaly [6].

Physical implication of the above gaugino mass is as follows. Non-vanishing F_T induces mass splitting between the bosonic and fermionic components of KK modes. These KK excited modes work as messenger fields which transmit the SUSY breaking effect to the visible sector. Therefore, we call this type of mediation mechanism as KK mediation.

Scalar soft masses are derived from wave-function renormalization $Z(\mu)_i$ of four-dimensional chiral multiplets Φ, whose kinetic term is written

$$\int d\theta^2 d\bar{\theta}^2 Z(\mu)_i |\Phi^i|^2. \tag{4}$$

For a chiral multiplet Φ^i, the one-loop renormalization-group equation for the wave-function factor Z_i is

$$\frac{d \ln Z_i}{dt} \;=\; \frac{1}{2\pi} N(\mu)(c_{KK}\alpha - a_{KK}\alpha_y) + \cdots \tag{5}$$

above the compactification scale. The coefficient c_{KK} is the quadratic Casimir invariant for the ϕ representation ($c_{KK} = 4C_2(R_\phi)$), and α_y is the Yukawa coupling squared, $\alpha_y = y^2/4\pi$, and the positive coefficient a_{KK} denotes a multiplicity of the Yukawa coupling in the one-loop anomalous dimension. In a similar way to the gaugino mass, by replacing $|M_c|^2 \to |T|^2$ in Z, we obtain the soft SUSY breaking mass for the scalar component,

$$m_i^2 \;=\; -\frac{\delta}{2}\gamma_i \left(\frac{F_T}{M_c}\right)^2 . \tag{6}$$

The scalar trilinear coupling term is also calculated from the wave-function renormalization,

$$A_i \;=\; -\gamma_i \frac{F_T}{M_c} \tag{7}$$

and the trilinear coupling in the Lagrangian is given by the sum of A_i's of the fields forming a superpotential coupling ($\mathcal{L} = -\sum A_i \phi^i \partial_{\phi^i} W(\phi)$). Note that when a μ-term generation mechanism is specified, the corresponding holomorphic scalar soft mass, the so-called B-term, is derived with the same form as eq. (7).

There are two points to notice. First, KK excited states generally belong to the multiplets of $N = 2$ or larger supersymmetry in the four-dimensional effective theory. The radiative corrections from the KK multiplets hence cancel out and SUSY breaking terms are not generated. For example, for bulk zero-modes, the gauge contributions disappear ($c_{KK} = 0$) because of the hypermultiplet non-renormalization theorem in unbroken $N = 2$ theories. The second point is how to describe Yukawa couplings among KK and boundary fields. We here assume that Yukawa couplings between KK excited states arise from combinations of trilinear and some higher-dimensional operators. On the other hand, Yukawa couplings involving boundary fields are given by local terms in higher-dimensional space [7].

Scalar trilinear couplings have no new CP-violating phases. The renormalization-group functions β and γ_i are determined by what types of multiplet live in the bulk and on the four-dimensional boundary. In other words, sparticle masses measured in future experiments can restrict the patterns of field configuration in the extra dimensions if the KK mediation is dominant. Note that in our scenario, the messenger interactions communicating SUSY breaking are related to the gauge and Yukawa couplings in the Standard Model, which are experimentally observed. Thus the particle and sparticle mass spectra correlate to each other though supersymmetry is broken.

We now examine our results for the SUSY breaking terms in an example, i.e. the model described in Ref. [4], in which the gauge and Higgs fields propagate in the bulk while the chiral matter multiplets live on a 3-brane. We calculate the soft terms in the approximation with the three gauge couplings and the top Yukawa coupling only. The beta-function coefficients are given by $b_{KK} = (-6, -3, 3/5)$ for $SU(3)$, $SU(2)$, and $U(1)$ respectively, and we have the gaugino masses,

$$M_3 : M_2 : M_1 \;\; = \;\; 10\alpha_3 : 5\alpha_2 : \alpha_1. \tag{8}$$

This ratio holds independently of the value of the compactification scale M_c and also remains unchanged under the renormalization-group running below M_c.

The Higgs soft masses vanish at the leading order. This is because of the absence of radiative corrections from the KK gauge messengers. For the squark and slepton masses, we first find that this setup can resolve the SUSY FCNC problem. Since the messenger Yukawa couplings are small for the first two generations, the soft masses are degenerate and the FCNC processes are suppressed. The sfermion masses are roughly on the order of the gaugino masses but the top Yukawa effect reduces the stop masses. Taking M_c near below the GUT scale ($\simeq 10^{16}$ GeV) and $\delta = 1$ for example, we obtain

$$m^2_{Q,u_{1,2}} \sim 1.7 m^2_{Q_3} \sim 4 m^2_{u_3} \sim m^2_d \sim 2 m^2_L \sim 2.5 m^2_e \sim 2 M^2_3 \tag{9}$$

at M_c. The relative ratios change through the renormalization-group evolutions down to low energy. Similarly we can calculate SUSY breaking terms for other models that some matter fields are in bulk.

To summarize we have shown that the non-vanishing F-term of the radius modulus gives a new mechanism for communicating SUSY breaking. There, KK excited states transmit the breaking effects to the visible sector via the gauge and Yukawa couplings, which are experimentally observed. The soft SUSY breaking parameters are expressed in terms of wave-function factors and the resulting spectrum is shown to have rich structure depending on how the Standard Model fields extend in the bulk. It is noted that the spectrum at the boundary scale in our scenario is in contrast to the case that there is a SUSY-breaking source somewhere in the extra dimensions and bulk fields directly couple to it. In that case, the bulk matter fields obtain sizable soft scalar masses, which are generally non-universal, but boundary fields have suppressed soft masses.

Acknowledgments

I would like to thank K. Yoshioka. This talk is based on the collaborating work with him. I also acknowledge the organizers of SI-2000 for their hospitality and encouragement, and participants for useful discussions.

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