Suppressing FCNC and CP-Violating Phases with Extra Dimensions[1]

JISUKE KUBO[(a,b)] and HARUHIKO TERAO[(b)]

(a) Instituto de Física, UNAM,Apdo. Postal 20-364, México 01000 D.F., México
(b) Institute for Theoretical Physics, Kanazawa University
Kanazawa 920-1192, Japan

It is widely accepted that the effects of supersymmetry breaking appear as soft supersymmetry breaking (SSB) terms. However, renormalizability allows to introduce more than 100 new parameters into the minimal supersymmetric standard model (MSSM). The problem is not only this large number of the independent parameters, but also the fact that the SSB terms induce large flavor-changing neutral current (FCNC) processes and CP-violating phases, which are severely constrained by precision experiments [1, 2, 3, 4, 5]. Therefore, the huge degrees of freedom involved in the soft-supersymmetry breaking (SSB) parameters have to be highly constrained in all viable supersymmetric models. This has been called the supersymmetric flavor problem. To overcome this problem, several ideas of SUSY breaking and its mediation mechanisms have been proposed; gauge mediation [6], anomaly mediation [7], gaugino mediation [8] and so on. The common feature behind these ideas is that the leading parts of the SSB parameters are given by flavor-blind radiative corrections. It is noted that the anomaly mediation and the gaugino mediation work on the assumption that the tree-level contributions for the SSB parameters at a fundamental scale $M_{\rm PL}$ are sufficiently suppressed, *e.g.*, by sequestering of branes for the visible sector and the hidden SSB sector, since there is no reason for these terms to be flavor universal. However, it has been argued recently [9] that such a sequestering mechanism cannot be simply realized in generic supergravity or superstring inspired models. An interesting way out from this problem is to suppress the tree-level contributions by certain field theoretical dynamics. There have been indeed several attempts along the line of thought, in which use has been made [10, 11, 12] that the SSB parameters are suppressed in the infrared limit in approximate superconformal field theories [13].

In [14], we proposed another possibility in more than four dimensions that flavor-blind radiative corrections are much more dominant than any other flavor non-universal contributions. At this meeting we would like to present our idea and results. The mechanism that we propose implements the power-law running of couplings [15, 16] in supersymmetric field theories with δ extra compactified dimensions and at the same time the infrared attractiveness of the SSB parameters [17]. We consider the simplest case in which only the non-Abelian gauge supermultiplet propagates in the $(4+\delta)$-dimensional bulk and the supermultiplets containing the

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matter and Higgs fields are localized at our 3-brane [16, 18, 19]. In this mechanism the gaugino mass M, which is assumed to be generated at the fundamental scale $M_{\rm PL}$ by some SUSY breaking mechanism, receives a correction proportional to $(M_{\rm PL}/M_{\rm GUT})^{\delta}$ at the grand unification scale $M_{\rm GUT}$, and more importantly induces dominant flavor-blind corrections to other SSB parameters. The most interesting finding is that the squared soft-scalar masses $(m^2)^i_j$ and the soft-trilinear couplings h^{ijk} become so aligned at $M_{\rm GUT}$ that FCNC processes and dangerous CP-violating phases are sufficiently suppressed. In this class of models, all the A-parameters h's, B-parameter B_H and soft-scalar masses m^2's in the minimal supersymmetric standard model (MSSM) are basically fixed as functions of the unified gaugino mass M and the μ-parameter μ_H, up to corrections coming from Yukawa interactions. Therefore, this class of models can not only overcome the supersymmetric flavor problem, but also have a large predictive power. Moreover, no charged sparticles become tachyonic in these models.

Let us be more specific. As mentioned, we assume that the $(4+\delta)$-dimensional gauge supermultiplet propagates in the bulk, and all the $N=1$ chiral supermultiplets $\Phi_i=(\phi_i,\ \psi_i)$ containing matters and Higgses propagate only in four dimensions. The gauge supermultiplet contains a chiral supermultiplet Γ in the adjoint representation, where we assume that δ is equal to one or two. We assign an odd parity to Γ so that it does not contain zero modes [16, 19], and do not have any interactions with Φ's. To simplify the situation we further assume that each extra dimension is compactified on a circle with the same radius R. The size of R is model dependent, but throughout this paper we assume that $M_{\rm GUT}=1/R$. With these assumptions, the boundary superpotential has a generic form

$$W(\Phi)=\frac{1}{6}Y^{ijk}\Phi_i\Phi_j\Phi_k+\frac{1}{2}\mu^{ij}\Phi_i\Phi_j, \quad (1)$$

and that the SSB Lagrangian $L_{\rm SSB}$ can be written as

$$-L_{\rm SSB}=\left(\frac{1}{6}h^{ijk}\phi_i\phi_j\phi_k+\frac{1}{2}B^{ij}\phi_i\phi_j+\frac{1}{2}\sum_{n=0}M\lambda_n\lambda_n+\text{h.c.}\right)+\phi^{*j}(m^2)^i_j\phi_i, \quad (2)$$

where λ_n's are the Kaluza-Klein modes of the gaugino, and we have assumed a unique gaugino mass M for all λ's.

We consider the renormalization group (RG) running of the parameters between the fundamental scale $M_{\rm PL}=M_{\rm Planck}/\sqrt{8\pi}\simeq 2.4\times 10^{18}$ GeV and $M_{\rm GUT}$. To see the gross behavior of the RG running, we first consider the contributions coming from only the gauge supermultiplet, because it is the only source responsible for the power-law running [15, 16] of the parameters under the assumptions specified above. In the flavor bases in which couplings of the gauginos are diagonal, only diagonal elements of the anomalous dimensions can contribute. We find the following set of the one-loop β functions in this approximation [16, 20]:

$$\Lambda\frac{dg}{d\Lambda}\ =\ =-\frac{2}{16\pi^2}C(G)G_\delta^2 g\ ,\ \Lambda\frac{dM}{d\Lambda}=-\frac{4}{16\pi^2}C(G)G_\delta^2 M, \quad (3)$$

$$\Lambda\frac{dY^{ijk}}{d\Lambda} = -\frac{2}{16\pi^2}(C(i)+C(j)+C(k))G_\delta^2 Y^{ijk}, \quad (4)$$

$$\Lambda\frac{d\mu^{ij}}{d\Lambda} = -\frac{2}{16\pi^2}(C(i)+C(j))G_\delta^2\ \mu^{ij}, \quad (5)$$

$$\Lambda\frac{dB^{ij}}{d\Lambda} = \frac{2}{16\pi^2}(C(i)+C(j))G_\delta^2(2M\mu^{ij}-B^{ij}), \quad (6)$$

$$\Lambda\frac{dh^{ijk}}{d\Lambda} = \frac{2}{16\pi^2}(C(i)+C(j)+C(k))G_\delta^2(2MY^{ijk}-h^{ijk}), \quad (7)$$

$$\Lambda\frac{d(m^2)^i_j}{d\Lambda} = -\frac{8}{16\pi^2}C(i)\delta^i_j G_\delta^2|M|^2, \quad (8)$$

where $G_\delta = gX_\delta^{1/2}(R\Lambda)^{\delta/2}$, and $X_\delta = \pi^{\delta/2}\Gamma^{-1}(1+\delta/2) = 2(\pi)$ for $\delta = 1(2)$ [16] [2]

The gauge coupling is denoted by g, and $C(G)$ stands for the quadratic Casimir of the adjoint representation of the gauge group G, and $C(i)$ for that of the representation R_i. It is easy to show that the evolution of Y^{ijk}, μ^{ij} and M are related to that of g as

$$M(M_{\rm GUT}) = \left(\frac{g(M_{\rm GUT})}{g(M_{\rm PL})}\right)^2 M(M_{\rm PL})\ ,\ Y^{ijk}(M_{\rm GUT}) = \left(\frac{g(M_{\rm GUT})}{g(M_{\rm PL})}\right)^{\eta_Y^{ijk}} Y^{ijk}(M_{\rm PL}), \quad (9)$$

$$\mu^{ij}(M_{\rm GUT}) = \left(\frac{g(M_{\rm GUT})}{g(M_{\rm PL})}\right)^{\eta_\mu^{ij}} \mu^{ij}(M_{\rm PL}), \quad (10)$$

where

$$\eta_Y^{ijk} = \frac{C(i)+C(j)+C(k)}{C(G)}, \quad \eta_\mu^{ij} = \frac{C(i)+C(j)}{C(G)}\ . \quad (11)$$

Therefore, these parameters can become very large if $g(M_{\rm PL})/g(M_{\rm GUT})$ is large. A rough estimate shows that

$$\frac{g(M_{\rm GUT}}{g(M_{\rm PL})} \simeq \left[\frac{C(G)X_\delta\alpha_{\rm GUT}}{\pi\delta}\right]^{1/2}\left(\frac{M_{\rm PL}}{M_{\rm GUT}}\right)^{\delta/2} \simeq 3.5(32) \text{ for } \delta = 1(2), \quad (12)$$

where we have used $\alpha_{\rm GUT} = 0.04,\ M_{\rm PL}/M_{\rm GUT} = 10^2,\ G = SU(5)$ to obtain the concrete numbers. These numbers should be compared with 1.3 in the corresponding four-dimensional case [17].

In contrast to $g,\ Y^{ijk},\ \mu^{ij},\ M$, the SSB parameters $B^{ij},\ h^{ijk}$ and $(m^2)^i_j$ have a completely different behavior. We find that the ratios of the SSB parameters to the gaugino mass M approach to their infrared attractive fixed points:

$$B^{ij}/M\mu^{ij} \rightarrow -\eta_\mu^{ij}\ ,\ h^{ijk}/MY^{ijk} \rightarrow -\eta_Y^{ijk}\ ,\ (m^2)^i_j/|M|^2 \rightarrow \frac{C(i)}{C(G)}\delta^i_j, \quad (13)$$

[2] X_δ is regularization scheme dependent. See [21] for a detailed analysis on the regularization dependence.

where η's are defined in (11). Note that so far no assumption on the reality of the SSB parameters has been made, and we recall that the phase of M and μ^{ij} can always be rotated away by a phase rotation that correspond to the R-symmetry and an appropriate rotation of the chiral superfields Φ, respectively. So, after these rotations, all the phases of M and μ^{ij} are transferred to those of Y^{ijk}, h^{ijk}, B^{ij} and $(m^2)^i_j$. Therefore, we may assume without loss of generality that M and μ^{ij} are real. We see from (13) that the low-energy structure is completely fixed by the group theoretic structure of the model. Furthermore, since h^{ijk} and $(m^2)^i_j$ become aligned in the infrared limit, *i.e.*, $h^{ijk} \propto Y^{ijk}$ and $(m^2)^i_j \propto \delta^i_j$, the infrared forms (13) give desired initial values of the parameters at $M_{\rm GUT}$ to suppress FCNC processes in the MSSM, and they predict that the only CP-violating phase is the usual CKM phase [3].

One can easily estimate how much of a disorder in the initial values at $M_{\rm PL}$ can survive at $M_{\rm GUT}$. Suppose that there exists an $O(1)$ disorder in $(m^2)^i_j/|M|^2$. Using the β functions (3) and (8), we find the deviation from (13) to be

$$\left(\frac{g(M_{\rm PL})}{g(M_{\rm GUT})}\right)^4 \left[\frac{(m^2)^i_j}{|M|^2}(M_{\rm PL}) - \frac{C(i)}{C(G)}\delta^i_j\right] . \tag{14}$$

Then inserting the value of $g(M_{\rm PL})/g(M_{\rm GUT})$ given in (12), we find that an $O(1)$ disorder at $M_{\rm PL}$ becomes a disorder of $O(10^{-2})$ and $O(10^{-6})$ at $M_{\rm GUT}$ for $\delta = 1$ and 2, respectively. Note that the off-diagonal elements of $(m^2)^i_j$ as well as the differences among the diagonal elements $\Delta m^2(i,j) = (m^2)^i_i - (m^2)^j_j$ (if $C(i) = C(j)$) belong to the disorder. However, their contributions to $(\delta_{ij})_{LL,RR}$ of [5] are less than $O(10^{-6})$ for $\delta = 2$, and therefore the most stringent constraints coming from the $K_S - K_L$ mass difference Δm_K and the decay $\mu \to e\gamma$ are satisfied [5]. In the case of five dimensions ($\delta = 1$) the suppression of the disorder will be sufficient, if the gauginos are much heavier than the sfermions [5]. [If we use $M_{\rm PL}/M_{\rm GUT} \sim 10^3$, then the suppression is much improved.]

Similarly, using (3) and (7), we obtain the deviation for the tri-linear couplings from (13) as

$$\left(\frac{g(M_{\rm PL})}{g(M_{\rm GUT})}\right)^2 \left[\frac{h^{ijk}}{MY^{ijk}}(M_{\rm PL}) + \eta^{ijk}_Y(M_{\rm PL})\right] , \tag{15}$$

where use has been made of (9). Suppose the tri-linear couplings to be order of MY^{ijk} at $M_{\rm PL}$. Then we find that

$$\left|\frac{h^{ijk}}{MY^{ijk}}(M_{\rm GUT}) + \eta^{ijk}_Y\right| \lesssim \left(\frac{g(M_{\rm PL})}{g(M_{\rm GUT})}\right)^{2+\eta^{ijk}_Y} . \tag{16}$$

Note that the phases of h^{ijk}/MY^{ijk} are also suppressed. In the case of $G = SU(5)$, $\eta^{ijk}_Y = 48/25(42/25)$ for the up (down) type Yukawa couplings. Using (12) again,

[3] Eq. (13) means that the phases of (h/MY) and $(B/M\mu)$ that cannot be rotated away approach zero in the exact infrared limit.

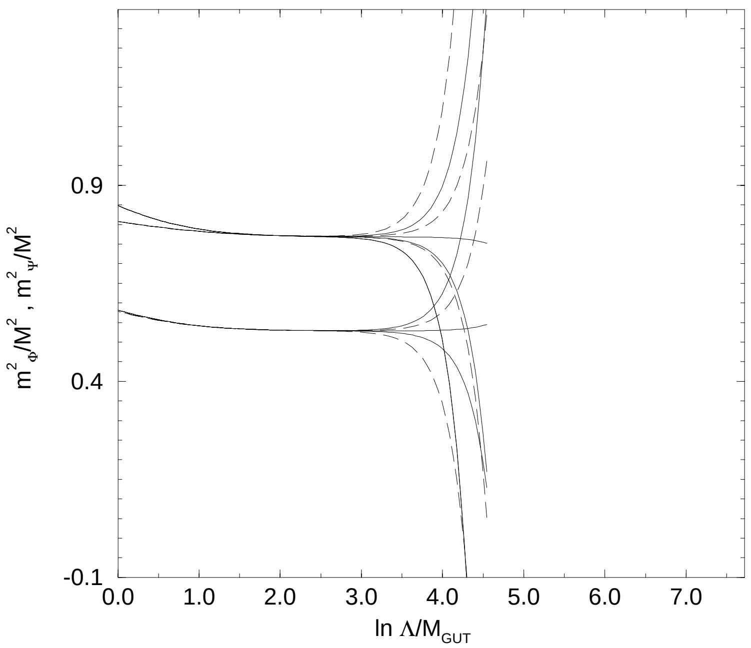

Figure 1: Infrared attractiveness of $m_5^2/|M|^2$ and $m_{10}^2/|M|^2$. The dashed (solid) lines correspond to the third (first two) generation(s). $m^2_{10^{1,2}}/|M|^2 > m^2_{10^3}/|M|^2 > m^2_{5^{1,2}}/|M|^2 \simeq m^2_{5^3}/|M|^2$ at $\Lambda = M_{\rm GUT}$.

we find that the right-hand side of (16) is $\sim 10^{-2(6)}$ for $\delta = 1(2)$. This disorder contributes, for instance, to $Im(\delta_{ii})_{LR}$ as well as $Re(\delta_{ij})_{LR}$ of [5]. Therefore our suppression mechanism can satisfy the most stringent constraints coming from the electric dipole moments (EDM) of the neutron and the electron and also from ϵ'/ϵ in the $K^0 - \bar{K^0}$ mixing [5]. Similarly the phases of the B-parameters, $B^{ij}/M\mu^{ij}$ are also suppressed.

In concrete examples, there will be logarithmic corrections to (13) to which the Yukawa couplings Y^{ijk} non-trivially contribute. How much the logarithmic corrections can amplify the disorder will be model-dependent. In [14] we performed detailed analyses on the logarithmic corrections in a GUT model based on $SU(5)$. Fig. 1, which is one of the main results of [14], shows the evolution of $m_5^2/|M|^2$ and $m_{10}^2/|M|^2$, respectively, in an obvious notation. The dashed lines correspond to the third generation. The differences $\Delta m^2_{10}(i,3)/|M|^2 = |m^2_{10^i} - m^2_{10^3}|/|M|^2$ with $i = 1,2$ directly contribute to, for instance, Δm_B in the $B - \bar{B}$ mixing as well as to $\tau \to e\gamma$ and $\tau \to \mu\gamma$. We find that $\Delta m^2_{10}(i,3)/|M|^2 \lesssim 0.04$ at $M_{\rm GUT}$, which means that $|(\delta^{l,u}_{13,23})_{RR}|, |(\delta^{d,u}_{13,23})_{LL}| \lesssim \times 10^{-2}$ at $M_{\rm GUT}$. Therefore, Δm_B and $\tau \to e\gamma$ and $\tau \to \mu\gamma$ are sufficiently suppressed. The differences $\Delta m^2_{10}(i,3)/|M|^2$ also contribute through the the mixing between the first two generations and the third generation to Δm_K

and $\mu \to e\gamma$. Assuming that the mass matrix of the up-type quarks is diagonal, and using the known values of Cabibbo-Kobayashi-Maskawa matrix V_{CKM}, we find that that $\Delta m_\Psi^2(i,3)/|M|^2 \lesssim 0.04$ does not cause any problems with the FCNC processes mentioned above. The difference of -0.04 in $m_\Psi^2/|M|^2$ also causes no problem for $b \to s\gamma$ [5]. We also studied the logarithmic contributions to the non-aligned part of h^{ijk}, which may contribute to the EDMs as well as ϵ'/ϵ in the $K^0 - \bar{K^0}$ system [5]. It is found that the disorder of the trilinear couplings caused by the Yukawa couplings are sufficiently suppressed to satisfy the constraints coming from these parameters.

We conclude that gauge interactions in extra dimensions can be used to suppress the disorder of the SSB terms at the fundamental scale so that the FCNC processes and dangerous CP-violating phases become tiny at lower energy scales. Moreover, no charged sparticles become tachyonic in this scenario of the SSB parameters. The suppression mechanism of the FCNC and CP-phases presented here does not properly work in four dimensions. Therefore, the smallness of FCNC as well as of EDM is a possible hint of the existence of extra dimensions.

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