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CP violation and extra dimensions

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Abstract. It is shown that new sources of CP violation can be generated in models with more than one extra dimension. In the supersymmetric models on the space-time $M^4 \times T^2/Z_2$, where the radius moduli have auxiliary vacuum expectation values and the supersymmetry breaking is mediated by the Kaluza–Klein states of the gauge supermultiplets, we analyze the gaugino masses and trilinear couplings for two scenarios and obtain the result that there exist relative CP violating phases among the gaugino masses and trilinear couplings.

It is well known that consistent weakly coupled (perturbative) superstring theories exist only in ten dimensions because of anomaly cancellations, and the extra six dimensions must be compactified so that the universe we "see" is 4-dimensional. In the weakly coupled heterotic $E_8 \times E_8$ string, which was phenomenologically the most interesting candidate among the known perturbative superstring theories, the compactification energy scale is the unification scale $M_{\mathrm{GUT}} \sim 2 \times 10^{16}$ GeV, which is too high to be probed. Recently, the study of strongly coupled superstring theories and duality opened the way which leads to the possibility to have large extra dimension compactifications due to the presence of the brane. For example, in the type I/I' string theory [1] the six compact dimensions are separated into ones tangent and transverse to the D-branes and the string scale can be made much smaller (e.g., 1 TeV) than the Planck scale if the physical volume of the transverse dimensions are very large [2]. Consistent with the compactification picture of string theories, various models with large extra dimensions have been proposed and their phenomenological implications in particle physics, gravity and astrophysics have extensively been examined [3] since the pioneering work of [4] was published.

On the other hand, the origin of CP violation has been one of main issues in high energy physics since the discovery of CP violation in the K_0–$\overline{K}_0$ system in 1964 [5]. The observation of $\mathrm{Re}(\epsilon'/\epsilon)$ by the KTeV collaboration [6] definitely confirms the earlier NA31 experiment [7]. This direct CP violation measurement in the kaon system can be accommodated by the CKM phase in the standard model within theoretical uncertainties. Recently, results on CP violation in B_d–$\bar{B}_d$ mixing have been reported by the BaBar and Belle Collaborations [8] in the ICHEP2000 Conference, which can also be explained in the standard model within both theoretical and experimental uncertainties. However, the CKM phase is not enough to explain the matter–antimatter asymmetry in the universe and gives a contribution to the electric dipole moments (EDMs) of the neutron and electron much smaller than the experimental bounds of the EDMs of electron and neutron. One needs to have new sources of CP violation in addition to the CP violation from the CKM matrix, which has been one of the motivations to search new theoretical models beyond the standard model, and examine their phenomenological effects.

Although vast phenomenological implications have been studied in various models with large extra dimensions, the CP violation[1] has not been examined so far. As emphasized above, one needs to have new sources of CP violation in models with extra dimensions for the models to be realistic enough to describe nature. In this letter, we shall show that it is possible to have a new source of CP violation due to the presence of extra dimensions. Assuming the 6-dimensional space-time manifold is $M^4 \times T^2/Z_2$, we calculate the gaugino masses and trilinear couplings for two scenarios in a framework where the radius moduli, which are related to the physical sizes of the extra dimensions, have auxiliary vacuum expectation values, and the supersymmetry breaking is mediated by the Kaluza–Klein states of gauge supermultiplets. We obtain the result that there are relative CP violating phases among the gauigno masses and trilinear couplings. Furthermore, it is easy to

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[1] There are papers in which the CP violation is discussed in models with extra dimensions [9]. However, in these models, the origin of CP violation is the complex vacuum expectation values of the Higgs fields, which is not directly related to extra dimensions

generalize our scenarios to supersymmetric models with more than two large extra dimensions and the CP violation can be induced by a similar mechanism. Therefore, we conclude that the new sources of CP violation can be generated in the supersymmetric models with more than one large extra dimensions where the radius moduli have auxiliary vacuum expectation values and the supersymmetry breaking is mediated by the Kaluza–Klein states of the gauge supermultiplets. Note that in 5-dimensional SUSY theories, there is no non-trivial CP violation induced due to the SUSY breaking because the overall phase can be rotated away [10,11].

For our purpose, we consider an $N = 1$ 6-dimensional supersymmetric (SUSY) theory compactified on T^2/Z_2. Upon compactification, in the 4-dimensional effective theory, we assume that there are two complex modulus superfields[2], X_1 and X_2, whose real parts are related to the radii R_1 and R_2 of the torus. In addition, we assume that the observable sector is located at one of the four different fixed points of the orbifold T^2/Z_2 and the SUSY breaking happens in the hidden sector which is located at the other fixed point and consequently is spatially separated from the visible sector [14]. We do not examine how the SUSY breaking happens and the moduli are stabilized[3], which are model dependent, in this letter. Instead, we parameterize the SUSY breaking by assuming that the modulus superfields have complex auxiliary vacuum expectation values, $\langle X_a \rangle = M_a + \theta^2 F_a$ with non-zero complex F_a, where $a = 1, 2$ and $M_a \sim R_a^{-1}$ which are smaller than the cutoff Λ of the effective theory. We shall consider two scenarios:

(A) the standard model gauge superfields all propagate in the bulk;
(B) the gauge superfields for $SU(3)$ and $SU(2) \times U(1)$ propagate in different extra dimensions. In scenario (A), we obtain the result that there are relative CP violating phases between the gaugino masses and the trilinear couplings, and among the trilinear couplings. In scenario (B), we also have different phases among the gaugino masses, in addition to those in scenario (A).

As pointed out in [12], before Weyl-rescaling there are no (non-derivative) direct couplings of the modulus X_a to the observable sector. The reason is that X_a can only couple to the higher-dimensional components of the energy-momentum tensor and the wave functions of the KK zero-mode fields do not depend on the extra-dimensional coordinates. The couplings of the KK (non-zero) modes of the gauge supermultiplets to the modulus fields will give a mass splitting in the SUSY multiplets. Thus, the KK excitations of the gauge supermultiplets act as messenger fields which transmit the SUSY breaking effect to the observable sector and consequently soft terms are generated at the quantum level in the 4-dimensional effective theory[4]. We shall use the method given in [15], i.e., use wave function renormalization, to derive the soft terms.

First, we consider scenario (A). Without loss of generality, we assume $M_2 < M_1$. The messenger mass spectra can be derived from the couplings of the KK excitations of the gauge supermultiplets to the background superfields

$$\int \mathrm{d}\theta^2 \mathrm{d}\bar{\theta}^2 \sum_{a=1}^{2} X_a^+ Tr e^{n_a V^{n_1,n_2}} X_a, \quad n_1, n_2 = 0, 1, 2, \cdots \tag{1}$$

where V^{n_1,n_2} is the KK mode for the gauge fields with mass

$$m_{n_1,n_2}^2 = \sum_{i=1}^{2} \frac{n_i^2}{R_i^2}. \tag{2}$$

The gaugino masses are given by

$$\tilde{M}_i(\mu) = -\frac{1}{2} \sum_{a=1,2} \frac{\partial \ln S_i(X_a,\mu)}{\partial \ln X_a}\bigg|_{X_a=M_a} \frac{F_a}{M_a}, \tag{3}$$

where μ is the energy scale, and $i = 1, 2, 3$, which correspond to the standard model gauge groups $U(1)$, $SU(2)$ and $SU(3)$, respectively. In addition, S_i is the gauge kinetic function, so it is a holomorphic function of X_a. Explicitly, the scalar component of S, $S_i(M_a,\mu)$, is

$$S_i(M_a,\mu) = \frac{\alpha_i^{-1}(M_a,\mu)}{16\pi} - \mathrm{i}\frac{\Theta_i}{32\pi^2}, \tag{4}$$

where $\alpha_i = g_i^2/4\pi$ with g_i being the gauge couplings and Θ_i is the topological vacuum angle. For simplicity, we will write $\alpha_i^{-1}(M_a,\mu)$ as $\alpha_i^{-1}(\mu)$. Once one knows the M_a dependence of $\alpha_i^{-1}(M_a,\mu)$ the X_a dependence of S follows from its holomorphy.

Taking into account the contributions of the KK excitations propagating in the extra dimensions, we express the running gauge couplings as

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(\Lambda) - \frac{(b_i - \tilde{b}_i)}{2\pi} \ln \frac{\mu}{\Lambda} - \frac{\tilde{b}_i}{4}\left[\frac{\mu^2}{M_1 M_2} - \frac{\Lambda^2}{M_1 M_2}\right], \quad \text{for } M_1 < \mu \le \Lambda, \tag{5}$$

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(M_1) - \frac{(b_i - \tilde{b}_i)}{2\pi} \ln \frac{\mu}{M_1} - \frac{\tilde{b}_i}{\pi}\left[\frac{\mu}{M_2} - \frac{M_1}{M_2}\right], \quad \text{for } M_2 < \mu \le M_1, \tag{6}$$

[2] The complex structure of the orbifold may be the source of the imaginary parts of X_1 and X_2

[3] In 5-dimensional theories the subject has been investigated; see, e.g., [10]

[4] Our framework is similar to that used in [11] which is called the "4D" approach in [13]. In [10] an effective theory in the rescaled basis is used (called the "5D" approach in [13]), which leads to gauge masses at tree level. The comparison between the two approaches has been written down in [13]. As pointed out in [13], the "discrepancy" is due to different assumptions for the boundary condition. The "4D" approach assumes that the 4-dimensional coupling at the cutoff scale of the effective theory is fundamental (no functional dependence on the compactification radius R), while the "5D" approach assumes that the 5-dimensional coupling at the cutoff scale of the effective theory is fundamental, so that the 4-dimensional coupling at the cutoff scale of the effective theory does depend on R

where Λ is the cutoff scale of the effective theory, and b_a and $\tilde{b}_a$ are the one-loop beta function coefficients in the MSSM and those arising from the massive gauge boson multiplets [16], respectively.

From (3), (5) and (6), it is straightforward to derive the gaugino masses:

$$\tilde{M}_i(\mu) = \frac{\alpha_i(\mu)}{4\pi}\tilde{b}_i\left[\frac{N(\Lambda)}{2}\left(\frac{F_1}{M_1}+\frac{F_2}{M_2}\right)\right.$$
$$\left. + \left(\frac{\pi}{2}-2\right)\frac{M_1}{M_2}\left(\frac{F_1}{M_1}-\frac{F_2}{M_2}\right)-\frac{F_2}{M_2}\right], \quad (7)$$

where $\mu < M_2$ and

$$N(\mu) \simeq \begin{cases} \pi\mu^2/M_1M_2, & \text{for } M_1 < \mu \le \Lambda, \\ 2\mu/M_2, & \text{for } M_2 < \mu \le M_1, \end{cases} \quad (8)$$

which is proportional to the surface of an ellipse with long axis R_2 and short axis R_1, indicating the number of KK excitations.

Trilinear terms, A_Q, can be derived from the wave-function renormalization of the chiral superfield Q, and can be expressed by

$$A_Q(\mu) = \sum_{a=1,2}\left.\frac{\partial \ln Z_Q(X_a, X_a^\dagger, \mu)}{\partial \ln X_a}\right|_{X_a=M_a}\frac{F_a}{M_a}, \quad (9)$$

where Z_Q is the wave-function renomalization of the chiral superfield Q, and can be solved from the differential equations

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\ln Z_Q = \sum_{j=1,2,3}\frac{C_Q(j)}{2\pi}\tilde{\gamma}_Q^j(\mu), \quad (10)$$

where

$$\tilde{\gamma}_Q^j(\mu) = \begin{cases} \alpha_j(\mu), & \text{for } \mu < M_2, \\ \alpha_j(\mu)N(\mu), & \text{for } M_2 < \mu < \Lambda, \end{cases} \quad (11)$$

where $C_Q(1), C_Q(2), C_Q(3)$ are the quadratic Casimirs of the Q representations of $U(1)$, $SU(2)$, $SU(3)$, respectively ($C_Q(j) = (j^2-1)/(2j)$ for an $SU(j)$ fundamental.). Note that the boundary condition $Z_Q(\Lambda)$ for the integration of (10) is independent of X_a, as $\alpha^{-1}(\Lambda)$ is, because the cutoff scale Λ is larger than the compactification scales M_1 and M_2.

To simplify the discussion, we only illustrate the contribution of one gauge interaction, i.e., one term in the sum in (10). Then we have

$$A_Q^i(\mu) = \frac{C_{qi}}{4\pi}\left\{\left(\alpha_i(M_2)\left(1-\frac{\tilde{b}_i}{b_i}\right)+\frac{\tilde{b}_i}{b_i}\alpha_i(\mu)\right)\right.$$
$$\times\left[\frac{N(\Lambda)}{2}\left(\frac{F_1}{M_1}+\frac{F_2}{M_2}\right)\right.$$
$$\left.+\left(\frac{\pi}{2}-2\right)\frac{M_1}{M_2}\left(\frac{F_1}{M_1}-\frac{F_2}{M_2}\right)-\frac{F_2}{M_2}\right]$$
$$\left.-\left(\frac{b_i}{\tilde{b}_i}-1\right)\left[\frac{1}{2\bar{D}^i}-\alpha_i(M_2)\right]\frac{F_1}{M_1}\right\}, \quad (12)$$

where

$$\bar{D}^i = \alpha^{-1}(\Lambda)+\frac{\tilde{b}_i}{4}\frac{\Lambda^2}{M_1M_2}-\frac{b_i-\tilde{b}_i}{4\pi}\ln\frac{M_1M_2}{\Lambda^2}$$
$$+\frac{b_i-\tilde{b}_i}{4\pi}. \quad (13)$$

For the case $M_1 = O(M_2)$, where the running between M_2 and M_1 can be neglected, the gaugino masses can be approximated by

$$\tilde{M}_i(\mu) = \frac{\alpha_i(\mu)}{4\pi}\tilde{b}_i\left[\frac{N(\Lambda)}{2}\left(\frac{F_1}{M_1}+\frac{F_2}{M_2}\right)\right.$$
$$\left.-\frac{\pi}{2}\frac{M_2}{M_1}\left(\frac{F_1}{M_1}-\frac{F_2}{M_2}\right)-\frac{F_2}{M_2}\right], \quad (14)$$

and the trilinear term reduces to

$$A_Q^i(\mu) \doteq \frac{C_{qi}}{b_i}\left[\left[1+\frac{\alpha_i(M_2)}{\alpha_i(\mu)}\left(\frac{b_i}{\tilde{b}_i}-1\right)\right]\tilde{M}_i(\mu)\right.$$
$$\left.+\left(\frac{b_i}{\tilde{b}_i}-1\right)\frac{\alpha_i(M_2)}{8\pi}b_i\frac{F_2}{M_2}\right]. \quad (15)$$

So, the gaugino masses and trilinear terms will have different CP violating phases when $N(\Lambda)$ is not much larger than one, so that the last term of (15) could compete with the first one. This implies that the CP violating effects are non-trivial[5]. In addition, we notice that among the trilinear terms, the relative CP violating phases can also be generated for the up-type quark, down-type quark, and leptons have different charges under the standard model gauge groups. Therefore, we conclude that the quantum effects can induce non-trivial CP violating phases. The assumption that F_a are complex is essential to obtain this conclusion, which is similar to the SUSY breaking and orbifold compactifications in supertring theory models [17] where complex F terms lead to complex soft terms. In those models the SUSY breaking is gravity-mediated, while it is mediated by KK modes in our models with extra dimsions. It is easy to see from (14) and (15) that one needs at least two independent phases (so, two radions corresponding to two extra dimensions) to make gauge masses and trilinear terms have physical CP violating phases which remain after R-transformation and appropriate redefinition of the fields. Otherwise, if there is only one extra dimension and consequently only one radion, one can have only one phase which can be removed by an R-transformation or appropriate redefinition of the Higgs superfield, i.e., there is no non-trival CP violating phase at all.

Now we turn to scenario (B), in which the $SU(3)$ gauge superfields and the $SU(2)\times U(1)$ gauge superfields live along R_1 and R_2, respectively. The calculations are

[5] A similar conclusion is obtained upon a heterotic string orbifold compactification in the papers by Acharya et al. and Bailin et al. in [17]. However, in contrast with heterotic string models where the compactification radius $R \ge 1/m_S$ ($m_S \sim 10^{17}$ GeV is the string scale) is very small, the extra dimensions can be large in our models with extra dimensions

straightforward and we only give the results here. The gaugino masses are

$$\tilde{M}_3(M_1) = \frac{\alpha_3(M_1)}{4\pi}\tilde{b}_3 N_1(\Lambda)\frac{F_1}{M_1}, \quad (16)$$

$$\tilde{M}_{1,2}(M_2) = \frac{\alpha_{1,2}(M_2)}{4\pi}\tilde{b}_{1,2} N_2(\Lambda)\frac{F_2}{M_2}, \quad (17)$$

where $N_{1,2}(\mu) \simeq 2(\mu/M_{1,2})$, indicating the number of excited KK modes.

As for the trilinear couplings A_Q, we obtain

$$A_D = \sum_{q=D,Q}\alpha_3(\mu)\frac{C_{q3}}{2\pi}N_1(\Lambda)\frac{F_1}{M_1} + \sum_{q=D,Q}\sum_{i=1,2}\alpha_i(\mu)\frac{C_{qi}}{2\pi}N_2(\Lambda)\frac{F_2}{M_2}, \quad (18)$$

$$A_U = \sum_{q=U,Q}\alpha_3(\mu)\frac{C_{q3}}{2\pi}N_1(\Lambda)\frac{F_1}{M_1} + \sum_{q=U,Q}\sum_{i=1,2}\alpha_i(\mu)\frac{C_{qi}}{2\pi}N_2(\Lambda)\frac{F_2}{M_2}, \quad (19)$$

$$A_E = \sum_{q=E,L}\sum_{i=1,2}\alpha_i(\mu)\frac{C_{qi}}{2\pi}N_2(\Lambda)\frac{F_2}{M_2}, \quad (20)$$

where $C_{U2} = C_{D2} = 0$.

If F_1 and F_2 had different phases, we obtain the result that the phase and magnitude of A_E are different from those of A_D and A_U from (18)–(20), and the phase and magnitude of $\tilde{M}_3$ are different from those of $\tilde{M}_1$ and $\tilde{M}_2$ from (16) and (17). In contrast with the scenarios based on string models with D-branes [18] where tree-level non-universal gaugino masses with relative phases have been obtained, in our scenario the SUSY breaking is mediated by KK modes and soft terms are generated at loop level.

In summary, we have shown by two specific scenarios that new sources of CP violation can be generated in the supersymmetric models on the space-time $M^4 \times T^2/Z_2$. In general, provided that the number of extra dimensions is larger than one, there are new sources of CP violation in the supersymmetric models where the moduli have auxiliary complex vacuum expectation values and the supersymmetry breaking is mediated by the Kaluza–Klein modes of gauge supermultiplets. It should be pointed out that in general supersymmetric theories, although in many cases the sizes of CP violating phases are strongly constrained by the experimental bounds on the electric dipole moments (EDMs) of the electron, neutron and ^{199}Hg atom, the possible cancellations among the different contributions to the EDMs can significantly weaken the upper bounds on the phases; therefore, the CP violating phases in supersymmetric theories can be allowed to be large [19]. By the way, it has been shown that the absence of CP violation in the standard model might be consistent with experiment, which implies that the gaugino masses and trilinear couplings A terms (as well as the Higgsino mass parameter μ) must be the entire source of CP violation [20] in this case. In our scenarios SM particles live in the 3-brane located at one of the fixed points of the orbifold. Obviously, the conclusions on new CP violation sources in our scenarios are independent of whether there is a CP violating phase in the CKM matrix, the SM CP violating phase. We may assume that there is an SM CP violating phase or there is no SM CP violating phase.

Another possibility to have CP violation is to construct the model in which the charge conjugation is conserved but the parity symmetry may be broken using extra dimensions [21]. Of course, it is interesting to search other new sources of CP violation in the models with large extra dimensions.

Note added: after finishing this work, we noticed the e-preprint by Branco et al. [22], in which the CP violation in the quark sector in the AS scenario is discussed.

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