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Radiative CP phases in supergravity theories

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Abstract

In this Letter, we point out that possible sources of CP violation originate from radiative corrections to soft terms which are ubiquitous in supergravity theories and also in other high-energy frameworks of supersymmetry breaking. With these radiative phases of gaugino masses and scalar couplings, a complex phase of Higgs holomorphic mass parameter is generated via renormalization-group running down to low energy. It is found that its phase value is mainly controlled by wino as well as gluino, which generally receive different radiative corrections to their complex phases, even if the leading part of mass parameters follow from the universality hypothesis. The radiatively generated phases are constrained by the existing experimental bounds on electric dipole moments, and may be detectable in future measurements. They are also found to be available for the cancellation mechanism to be worked.

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Low-energy supersymmetry (SUSY) is one of the most attractive candidates for the fundamental theory beyond the standard model (SM). It provides various successful applications such as the stability of mass hierarchy [1] and the gauge coupling unification from the precise electroweak measurements [2]. However, supersymmetry must be broken due to the absence of experimental signatures below the electroweak scale. Breaking supersymmetry generally gives rise to phenomenological problems caused by the existence of supersymmetric partners of the SM fields. One of these problems is the flavor and CP violation [3]. It is usually assumed to overcome the flavor problem that SUSY-breaking masses of squarks and sleptons are degenerate within the three generations [4]. Such a universality is often discussed in supergravity theory [5]. With this universal assumption, it is clear that the fermion and sfermion mass matrices are simultaneously diagonalized by superfield rotations and hence flavor-violating processes are suppressed. It is also noticed that the universality implies there is no CP phase in SUSY-breaking scalar masses.

An important point is that CP violation occurs even in the absence of flavor violation. To see this, we briefly describe conventional treatment of other four types of parameters in softly-broken supersymmetric theories. First, gaugino masses are usually assumed to take a universal value at some high-energy scale. This may be motivated by the existence of grand unification of the SM gauge groups. Therefore one

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has an overall complex phase of gaugino masses. The renormalization-group evolution (RGE) of gaugino masses down to low energy does not change their complex phases. Since scalar trilinear couplings As carry the flavor indices, the universal assumption is also adopted for the A parameters to suppress flavor-changing rare processes. A simply way to realize the universality is to have vanishing A parameters at high-energy scale. The RGE of A's is governed by gaugino masses and therefore generates flavor-blind A terms. Such a scenario may be realized, e.g., by making a separation between SUSY-breaking and visible sectors. The remaining two parameters are concerned with the Higgs sector; the supersymmetric Higgs mass μ and the holomorphic SUSY-breaking mass B. Note that the former suffers from the so-called μ problem, that is, how to obtain an electroweak-scale μ parameter. Due to this and related problems, the situation is rather complicated than the others, and in particular, the sequestering does not work unlike A parameters (see, however, dynamical relaxation mechanisms, for example, [6]). We will simply assume in this Letter that μ is settled to have a right order of magnitude.

Working with the hypothesis of flavor universality of scalar masses, we thus obtain four complex parameters in supersymmetric theories; a universal gaugino mass M, a common scalar trilinear coupling A, supersymmetric Higgs mass μ, and Higgs mixing mass B. Given that the $U(1)_{\mathrm{R}}$ and Peccei–Quinn rotations can remove two of these four phases, have we two CP-violating parameters A and B, where M and $B\mu$ are taken to be real. No more phases cannot be rotated away by field redefinition. The severest upper bounds on these two complex phases come from the experimental results such as non-observation of sizable electric dipole moments (EDM) of the electron [7], neutron [8] and mercury atom [9]

$$d_{\mathrm{e}} < 4.3 \times 10^{-27}\ \mathrm{e\,cm}, \qquad d_{\mathrm{n}} < 6.3 \times 10^{-26}\ \mathrm{e\,cm},$$
$$d^{\mathrm{C}}_{\mathrm{Hg}} < 7 \times 10^{-27}\ \mathrm{cm}. \tag{1}$$

Here the experimental bound on the EDM of the mercury atom has been translated into that of the chromo-electric dipole moment $d^{\mathrm{C}}_{\mathrm{Hg}}$ [10]. For example, in the minimal supersymmetric standard model, A and B are required to satisfy $\arg A \lesssim 10^{-1}$ and $\arg B \lesssim 10^{-2}$ in the basis where gaugino masses are real, when the SUSY-breaking masses are a few hundred GeV.

In this Letter, we examine CP-violating phenomena in supergravity theories. In particular, we point out the importance of radiatively-generated complex phases of SUSY-breaking parameters, which often arise inevitably in various frameworks of high-energy supersymmetry breaking.

SUSY-breaking parameters X in general consist of two parts;

$$X = X_0 + \delta X. \tag{2}$$

The first term in the right-hand side is the leading contribution which arises from direct coupling to SUSY-breaking dynamics. We take a simple and conservative assumption that the leading part, e.g., of A_i's, can generally be non-universal in size but its phase is universal. The second term δX means sub-leading corrections in the sense that an absolute value of δX is suppressed compared to the leading part. The point is that these two contributions are likely to have different origins and hence independent phase values. In fact, this is indeed the case without additional assumptions and/or specific dynamics of supersymmetry breaking. After re-phasing out the overall complex phase of the leading part, we have a non-vanishing amount of total phase of parameter

$$\arg X = \frac{1}{X_0}\,\mathrm{Im}\,\delta X + O\left(\left|\frac{\delta X}{X_0}\right|^2\right), \tag{3}$$

which cannot be rotated out anymore. The correction δX gives only a few effects on mass spectrum at the electroweak scale and therefore have been neglected before. However, as we will see below, the radiatively-induced phases are observable in CP-violating phenomena as the experimental results tightly constrain complex phases.

Among various SUSY-breaking parameters, we discuss in this Letter the gaugino masses M_i ($i = 1, 2, 3$) in supersymmetric standard models. Most generally, possible corrections δM_i have different phase factors, which cannot be re-phased out obviously and may cause large CP violation. A bit restricted form of corrections we will encounter is that δM_i have a universal phase but their sizes are different to each other. As an example, consider the SUSY-breaking masses

of the form

$$M_i = M_0 + \frac{c_i g^2}{16\pi^2} F, \tag{4}$$

where g is some coupling constant and F parameterizes a typical size of SUSY breaking. In the right-hand side of the equation, the second term denotes the subleading part compared to the leading universal part M_0. In this case, non-vanishing complex phases appear as interference of the two parts. It is found from Eq. (3) that the resultant complex phases at SUSY-breaking scale are given by

$$\arg M_i \simeq \frac{c_i g^2}{16\pi^2} \operatorname{Im}\left(\frac{F}{M_0}\right). \tag{5}$$

Thus radiative corrections to SUSY-breaking parameters, if there exists, generally become origins of CP breaking. The criterion for obtaining non-vanishing phases is the existence of corrections which are (i) ubiquitously seen in the theory and (ii) different in size between the three SM gauginos. If a theory unavoidably receives such corrections, one is forced to suppose extra assumptions to control sizable CP violation.

The relative phases of gaugino masses like Eq. (5) are detectable in the measurements of EDMs [11]. At the electroweak scale, that can provide upper bounds on CP-violating phases of SUSY-breaking parameters. Among them, the severest constraint is imposed on a phase of Higgs mixing parameter B. To estimate a phase value, it is essential to fix the Higgs mixing mass at some cutoff scale at which the SUSY-breaking parameters are generated, and solve the RGEs down to the electroweak scale. The RGE for B is given by

$$\frac{dB}{dt} = \frac{1}{16\pi^2}\left(6y_t^2 A_t + 6y_b^2 A_b + 2y_\tau^2 A_\tau + 6g_2^2 M_2 + \frac{6}{5} g_1^2 M_1\right), \tag{6}$$

where $y_{t,b,\tau}$ are the Yukawa couplings of the top, bottom and tau, and $g_{1,2}$ the $U(1)_Y$ and $SU(2)_W$ gauge couplings, respectively. A low-energy value of B parameter depends on SUSY-breaking parameters at an initial high scale. Its dependence is described by the approximate solution to the RGE

$$B(t) \simeq B(0) + \left(\frac{3}{8\pi^2}\frac{y_t^2(t)}{E(t)}\int_0^t E(u)\,du\right) A_t(0) + \sum_{i=1,2,3}\left(\frac{t}{8\pi^2} r_i g_i^2(t) + \frac{3}{8\pi^2}\frac{y_t^2(t)}{E(t)}\int_0^t \frac{u}{8\pi^2} r_i' g_i^2(u) E(u)\,du\right) M_i(0), \tag{7}$$

where the effects of small Yukawa couplings have been neglected. We have assumed no unification assumption of gaugino masses at the initial scale, which is relevant to the current interest of non-universal corrections. The coefficients r's are fixed by the charges of corresponding fields and given by $r_i = (3/5, 3, 0)$ and $r_i' = (13/15, 3, 16/3)$ for $U(1)_Y \times SU(2)_W \times SU(3)_C$. The function E is defined by $E(u) = \prod_{i=1,2,3}[g_i(0)/g_i(u)]^{2r_i'/b_i}$. We can understand the result of B parameter as follows. The RGE correction to B at the electroweak scale is mainly controlled by M_2, M_3 and A_t. In the direct contribution from RGE running, the imaginary parts of M_2 and A_t affect the B parameter. On the other hand, since a low-energy value of A_t is dominated by the strong gauge dynamics, so is its phase value. Thus the M_3 phase comes into play in the low-energy B parameter. An initial value of B also directly appears in the fitting formula. Such behaviors are also easily understood from the RG-invariant relation among B, A_t and M_i [12]. In Table 1, we present a list of one-loop numerical coefficients in the fitting formula for the electroweak scale B parameter and the EDMs against imaginary parts of SUSY-breaking parameters at the initial scale. Here we assume the universal hypothesis defined above and take $|M| = m_0 = 300$ GeV and $A = B = 0$ as the leading part of parameters at the cutoff scale. It is interesting that the phase correction to B comes from the gluino mass as well as the wino. A total amount of corrections is given by the interference of these two sizable corrections (the photino mass effect is negligible due to a tiny gauge coupling). For an illustration, consider the leptonic EDMs. For not a so small value of $\tan\beta$, SUSY radiative corrections are dominated by a one-loop graph in which the chargino and scalar neutrino propagate

Table 1
The fitting formulae for the imaginary part of B parameter and the various EDMs at the electroweak scale. They depend on the corrections to SUSY-breaking mass parameters at high-energy scale, indicated in the first line. For instance, $d_e = -3.6 \times 10^{-26} \times \mathrm{Im}\,\delta B + 1.2 \times 10^{-26} \times \mathrm{Im}\,\delta A_t + \cdots$. In the table, we take $|M| = m_0 = 300$ GeV and $A = B = 0$ as the leading part at the cutoff scale. In our notation, a scalar trilinear coupling constant is defined as $A \times y$, where y is a corresponding Yukawa coupling

	$\mathrm{Im}\,\delta B$ (GeV)	$\mathrm{Im}\,\delta A_t$ (GeV)	$\mathrm{Im}\,\delta M_3$ (GeV)	$\mathrm{Im}\,\delta M_2$ (GeV)
$\mathrm{Im}\,B_{\mathrm{EW}}$ (GeV)	1	-0.32	-0.49	0.36
d_e	-3.6×10^{-26}	1.2×10^{-26}	1.8×10^{-26}	-1.7×10^{-26}
d_n	-3.3×10^{-25}	1.1×10^{-25}	1.6×10^{-25}	-1.5×10^{-25}
$d_{\mathrm{Hg}}^{\mathrm{C}}$	-1.2×10^{-25}	3.7×10^{-26}	4.7×10^{-26}	-4.4×10^{-26}

in the loop. This is therefore proportional to $M_2\mu$ and its phase is given by $\arg(M_2 B^*)$. The experimental results tell us that this quantity must be smaller than 10^{-2}. From Table 1, one can see that the EDM measurements provide severe constraints on supersymmetric standard models. Given the experimental bounds (1), the $d_{\mathrm{Hg}}^{\mathrm{C}}$ constraint tends to be more restrictive than the others. However, note that we use the chiral quark model for calculating the EDMs, where there are uncertainties due to some model dependences and QCD corrections to the EDMs. The QCD uncertainties also exist in the estimation of the mercury EDM.

We thus find that the phase of Higgs mixing parameter at an observable low scale is induced by radiative corrections through the RGE running, and inevitably appears at that scale. Such a CP-violating phase can be large enough to be detectable at the measurements of EDMs. It is also noted that the A_t phase at an initial scale is restricted as at comparable level as the B parameter.

We now discuss several examples where radiative corrections to SUSY-breaking parameters naturally appear. If supersymmetry is valid up to high-energy regime, it is extended to include the gravity. The gravity multiplet then becomes to mediate SUSY breaking to the visible sector via super-Weyl anomaly, called the anomaly mediation [13]. It is important that the contribution of the anomaly mediation is always manifest in supergravity framework. Moreover, its magnitude is given in terms of anomalous dimensions of corresponding fields and is different to each other. Such a contribution has been dropped in the gravity mediation scenarios because of relative loop suppressions compared to direct contribution from SUSY-breaking dynamics. However CP violation is enough sensitive to complex phases including sub-leading contributions, as we noted before.

To estimate CP violation, we assume that the leading spectrum follows from the universality at an initial scale;

$$M_i(0) = M_0, \qquad A_i(0) = A_0, \qquad B(0) = B_0, \tag{8}$$

and the degenerate sfermion masses m_0. They come from, e.g., the hidden sector SUSY breaking in supergravity models. In the following analysis, we take $A_0 = B_0 = 0$, for simplicity. On the other hand, the ubiquitous radiative corrections appear via the anomaly mediation whose contributions are

$$\delta M_i = \frac{\beta_i}{g} F_\phi, \qquad \delta A_i = \gamma_i F_\phi, \qquad \delta B = 0, \tag{9}$$

where β_i and γ_i are the gauge beta functions and anomalous dimensions of matter fields, respectively. Here δB is simply assumed to be zero because of unspecified origin of Higgs mass parameters. This assumption does not change our results unless some miraculous cancellation occurs among complex quantities. F_ϕ is the auxiliary component of the compensator multiplet and gives an order parameter of SUSY breaking. Requiring a vanishing cosmological constant, F_ϕ is related to other (hidden sector) F terms which generate the leading part spectrum, then $|F_\phi| \sim |M_0|$. Even if there is no CP violation in each part of X or δX, relative phases generally appears due to the different coefficients in δX's. Interestingly, the differences of gauge beta functions are non-zero and model independent as long as preserving the gauge coupling unification. In Fig. 1, we present a result of numerical analysis of various EDMs in supergravity scenarios modified by anomaly mediation. Figures show that the existing experimental results can detect anomaly-mediated corrections to gaugino masses, and in turn,

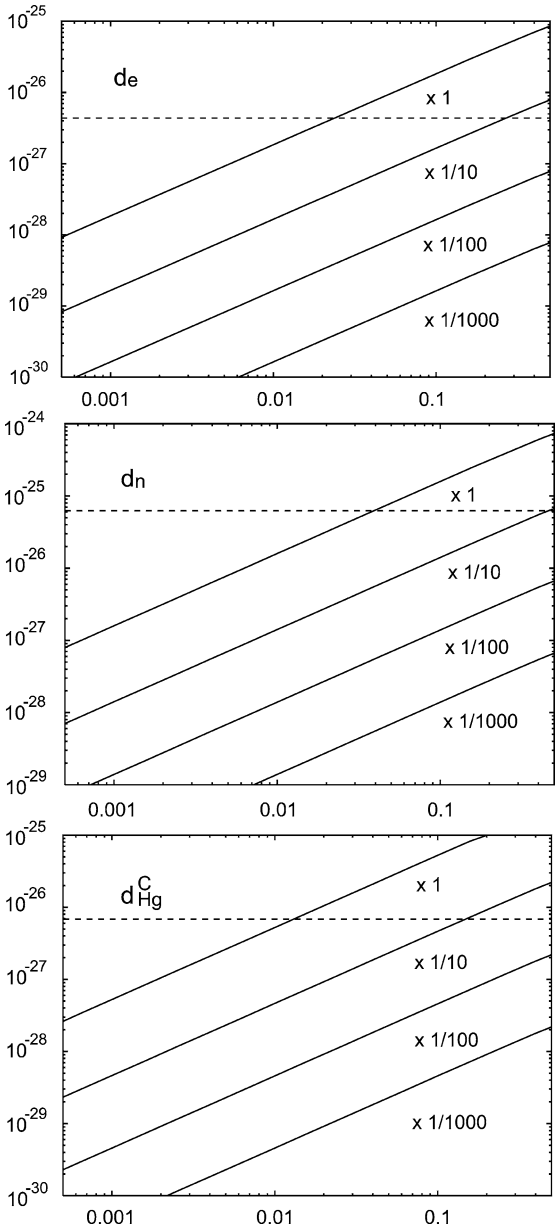

Fig. 1. The EDMs in supergravity theory corrected by anomaly-mediated contribution to gaugino masses. The horizontal axis in each figure is a relative phase of F_ϕ to the leading universal part. The numbers in the figures denote relative sizes of the corrections. The initial values of parameters are same as in Table 1. The dashed lines show the current experimental bounds.

put strong restrictions on the sizes and phases of the corrections. The expected improvements in experimental precision could give more information about new-physics contribution such as super-Weyl anomaly and would more severely constrain the model structure to a non-trivial form.

If the generation of too large complex phases were inevitable, non-trivial dynamics and/or hypothesis would have to be introduced for the models to be viable. A naive way is to assume that all parameters involved in SUSY-breaking dynamics are real. For example, consider the gravity mediation to induce the leading part of SUSY breaking. In supergravity, tree-level gaugino masses come from gauge kinetic functions $f_i = 1 + \kappa_i Z_i + O(Z^2)$, Z_i denotes a hidden multiplet responsible for SUSY breaking. At this level, the coefficients κ_i are required to have a common phase factor, which can be rotated away by $U(1)_{\mathrm{R}}$ symmetry. However, a combined analysis with anomaly-mediated corrections means a stronger condition that κ_i must be real without any field redefinition. It is similarly found that when the leading part is described by the gaugino mediated contribution [14], a similar condition must be imposed, that is, one just has to adopt CP-conserving SUSY-breaking dynamics. On the other hand, the CP phases from (5) allow two types of possible dynamical resolutions. In the first case, the phase of leading part is aligned at a high accuracy to the corrections. One way to realize this situation is the deflected anomaly mediation scenario [15]. There, SUSY breaking of leading part is induced by F_ϕ effects and the phases are automatically aligned.[1] The second is a hierarchy among SUSY-breaking F terms. If the pure anomaly mediation is the dominant source of SUSY breaking, i.e., $M_0 \ll F_\phi$, CP-violating phases are suppressed. An example of the inverse type of hierarchy is achieved in gauge mediated SUSY breaking scenarios [18]. Gauge mediated spectrum is roughly determined by F_X/M_X where M_X denotes the mass scale of messenger fields. Therefore the contamination by anomaly mediated contribution $|F_\phi| \sim |F_X/M_{\mathrm{Pl}}|$ is naturally suppressed for low-scale SUSY breaking $M_X \ll M_{\mathrm{Pl}}$. In this case, the gravitino becomes much lighter than gauginos.

Sizable CP-violating corrections could appear in various other frameworks than the anomaly media-

[1] An alignment mechanism of CP phases will be discussed elsewhere [16], which includes as a simple example SUSY breaking with the radion stabilization considered in Ref. [17].

tion. It is known that SUSY breaking in string-inspired supergravity is described in terms of two modulus fields; the dilaton and the overall modulus. The leading contribution comes from the dilaton F term which is automatically flavor and CP blind. On the other hand, (in weakly-coupled theory) the overall modulus gives one-loop threshold corrections to gaugino masses. Moreover their sizes depend on gauge beta functions as well as the Green–Schwarz coefficient. Therefore the criterion to have non-vanishing phases is certainly satisfied. As a result, the phases of the two modulus F terms must be aligned with some underlying principle. CP phases from the overall modulus are discussed, e.g., in [19]. Another example is grand unified theory (GUT). Gauge coupling unification is known as one of the motivations for considering supersymmetry as a promising candidate of new physics. Then unified gauge group is thought to necessarily break into the SM group at the GUT scale. This is accompanied by decoupling some heavy particles, which are the GUT partners of the SM fields. At this stage, threshold corrections to SUSY-breaking parameters are induced by these heavy particles circulating in the loops [20]. It is interesting that these corrections exist in any GUT model and give rise to one-loop differences between the three gaugino masses, because heavy particle spectrum is GUT breaking and split three gaugino masses. As in the case of anomaly mediation, the corrections generally lead to model-dependent signatures of EDMs at low energy, which in turn might give an evidence of grand unification. Radiative phases may also appear at low-energy thresholds [21].

Finally we mention to another interesting consequence of radiative phases that they work to ameliorate the CP problem with cancellations among various diagrams. The cancellation mechanisms with possible $O(1)$ phases have been discussed in [22]. There non-universal spectrum and/or rather large A-term contributions are typically assumed to suppress the EDMs. We now have relative phases of gaugino masses among the three gauge groups. They are induced radiatively in a controllable way once high-energy models are fixed. The phase of the Higgs B parameter is also generated via the RGE evolution down to the electroweak scale, which phase is described by those of gauginos. Here we will give a rough estimation of cancellation of EDMs only in the first-order approximation, and a complete analysis will be presented elsewhere. First consider the neutron EDM. In the chiral quark model we adopt in this Letter, the neutron EDM is given by $d_{\mathrm{n}} = 4d_{\mathrm{d}}/3 - d_{\mathrm{u}}/3$, where the EDMs of the individual quarks $d_{\mathrm{u,d}}$ come from the three contributions; the electric and chromoelectric dipole moments and the gluonic dipole moment. The down-quark electric dipole moment gives the dominant part of the neutron EDM for most parameter space except for the case of large μ parameter and small gaugino masses. Accordingly, severe limits on the CP phases can be avoided if d_{d} vanishes at the electroweak scale, which results in

$$g_3^2 \operatorname{Im}(M_3 B^*) = g_2^2 \operatorname{Im}(M_2 B^*) N_{\mathrm{n}}\big(|M_2|, |M_3|, m_{\tilde{Q}}^2, |\mu|\big). \tag{10}$$

We have neglected higher-order terms of the QED gauge coupling and A_{d} term, which is relevant for the case of large $\tan\beta$ or $A_{\mathrm{d}} \ll \mu$ (or $\operatorname{Im}(M_3 A_{\mathrm{d}}^*) \simeq 0$). The real function N_{n} depends on model parameters and its explicit expression can be found, e.g., in [22]. A similar estimation for the electron EDM leads to a cancellation condition

$$g_2^2 \operatorname{Im}(M_2 B^*) = g_1^2 \operatorname{Im}(M_1 B^*) N_{\mathrm{e}}\big(|M_1|, |M_2|, m_{\mathrm{L}}^2, m_{\mathrm{e}}^2, |\mu|\big). \tag{11}$$

The detailed form of N_{e} is also found in [22]. In Fig. 2, we show typical cancellation conditions (10) and (11) for various values of N_{n} and N_{e}, which depend on model parameters. For an illustration, we take a single source of radiative corrections, that is, a common complex phase of the corrections to gaugino masses and A parameters. Even in this restricted case, one can see that the cancellations do work for wide ranges of parameter space. As an example, let us consider the corrections from anomaly mediation discussed before. One first notices that their contribution is determined by gauge beta functions and leads to a definite model prediction of induced phases. In Fig. 2, these anomaly-mediated corrections are expressed by the lines which are determined by ratios of gauge beta functions, that are fixed only by field content of the models. A requirement of CP conservation therefore could distinguish models. A simultaneous suppression of various EDMs may be possible for more realistic option with non-universal radiative corrections. A numerical inspection including the $d_{\mathrm{Hg}}^{\mathrm{C}}$ constraint as well

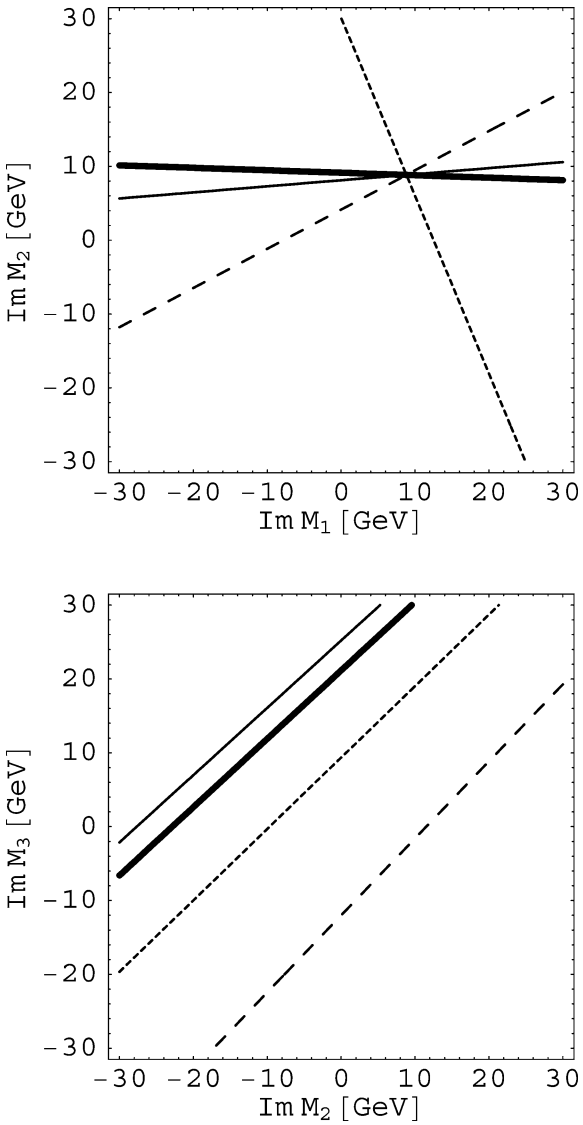

Fig. 2. Typical cancellation lines for the EDMs of the electron (upper graph) and the neutron (lower graph). The bold, solid, dashed and dotted lines correspond to $N_e = 0.1, 1, 3, 10$ and $N_n = 1, 3, 10, 30$, respectively. The corrections $\delta A = 20i$ and $\delta M_3 = 20i$ (upper) and $\delta M_1 = 20i$ (lower) are assumed. The other initial values of parameters are same as in Table 1.

shows that the experimental EDM constraints actually allow $\arg(M_i B^*) \sim 0.1$–0.5 which are an order of magnitude larger than naive bounds of phase values. The complete analysis rather depends on SUSY-breaking mass spectrum and we leave it to future investigation, including collider implications of such large CP phases. Anyway radiative corrections provide a dynamical justification to adopt the cancellation mechanism and can make the models to be viable.

We pointed out in this Letter that

- At high-energy scale, gaugino masses and scalar soft terms receive various radiative corrections in supergravity theories. It is important that complex phases of these corrections can generally differ from the leading part, which phases induce small but sizable non-vanishing phases of total soft parameters.
- The radiatively-induced phases are actually detectable in EDM measurements via RG evolution of the phase of Higgs mixing B parameter down to low energy. A RG analysis strongly constrains the complex gaugino masses and scalar top trilinear coupling at high-energy scale (Table 1).[2] These facts give important constraints on models of SUSY breaking.
- A cancellation mechanism for suppressing SUSY CP violation can be worked due to radiative corrections with non-vanishing phases.

In conclusion, radiative corrections to complex phases of SUSY-breaking parameters have important consequences for low-energy phenomenology. Experimental measurements of CP-violating quantities would select possible model structure through the radiative phase corrections. It is also possible to cancel out various diagrams of CP violation as a prediction of the models with controllable phase parameters.

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[2] After submitting the Letter, we were aware that the constraint on the phase of A_t was discussed in Ref. [23].

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