Effect of supersymmetric CP phases on the $B \to X_s \gamma$ and $B \to X_s l^+ l^-$ decays in the minimal supergravity model

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Abstract

We investigate the effect of supersymmetric CP violating phases on the $B \to X_s \gamma$ and $B \to X_s l^+ l^-$ decays in the minimal supergravity model. We show that the phase of the trilinear scalar coupling constant for top squarks is strongly suppressed and aligned to that of the gaugino mass due to a renormalization effect from the Planck scale to the electroweak scale. As a result, the effect of supersymmetric CP violating phases on the $B \to X_s \gamma$ and $B \to X_s l^+ l^-$ decays are small taking into account the neutron and the electron electric dipole moment constraints. For the $B \to X_s \gamma$ decay, the amplitude has almost no new CP violating phase and the direct CP asymmetry is less than 2%. For the $B \to X_s l^+ l^-$ decay, the branching ratio can be sizably different from that in the standard model only when the sign of the $B \to X_s \gamma$ amplitude is opposite to that in the standard model.

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The origin of the CP violation is one of main issues in current particle physics. In the standard model (SM) the CP violation is originated from the phase of the Kobayashi-Maskawa matrix [1]. A new source of CP violation can appear in models beyond the SM.

Among various models beyond the SM, the minimal supersymmetric SM (MSSM) is one of the most promising candidate. The MSSM contains many new parameters, i.e. soft supersymmetry (SUSY) breaking parameters. If we allow arbitrary soft SUSY breaking parameters, too large flavor changing neutral current (FCNC) processes, such as $K^0\bar{K}^0$ mixing, appear. In the minimal supergravity (mSUGRA), soft SUSY breaking parameters are assumed to have universal structures at the Planck scale, so that these dangerous FCNC processes are suppressed.

In the mSUGRA, there is no intrinsic reason that these SUSY breaking parameters should be real and there are four new CP violating phases, i.e. phases of the gaugino mass, the higgsino mass parameter, the SUSY breaking Higgs boson mass, and the trilinear scalar coupling constant, of which two combinations are physically independent. These phases induce the neutron and electron electric dipole moments (EDMs). There are many works on the constraints of the EDMs in the MSSM [2] as well as in the mSUGRA [3–6]. It is shown that in the mSUGRA, if we take a phase convention that the trilinear scalar coupling constant and the higgsino mass parameter have phases, $\phi_A$ and $\phi_\mu$, respectively, the constraint on $\phi_\mu$ is much stronger than that on $\phi_A$ [4–6].

It is known that the $B \to X_s\gamma$ process gives strong constraint on the SUSY model. In particular, in Ref. [4], rare $B$ decays, such as $B \to X_s\gamma$ and $B \to X_s l^+l^-$, are studied in the mSUGRA without new CP violating phases. For the $B \to X_s\gamma$ decay, the SUSY contributions interfere with the amplitude in the SM either constructively or destructively, and the amplitude can change its sign. It is also shown that the $B \to X_s l^+l^-$ branching ratio is enhanced compared to the SM prediction if the sign of the $B \to X_s\gamma$ amplitude is opposite to that in the SM. It is interesting to investigate the effect of the CP violating phases on various $B$ decays. In Ref. [1] one of the authors (T.N.) analyzed effect of the SUSY CP violating phase on $B^0\bar{B}^0$ mixing, and showed that the effect is small. Recently a possibility of large direct CP asymmetry in the $B \to X_s\gamma$ process is studied in the MSSM [8, 9], and MSSM with SUGRA-motivated SUSY breaking terms [10].

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In this letter we investigate the effect of the SUSY CP violating parameter on rare $B$ decays, $B \to X_s \gamma$ and $B \to X_s l^+l^-$, in the mSUGRA. In our analysis we require the universality of SUSY breaking terms at GUT scale and explicitly solve the renormalization group equations (RGEs) to determine the masses and the mixings of SUSY particles and also require the condition for the radiative electroweak symmetry breaking. We confirm that $\phi_\mu$ is strongly constrained by the neutron and electron EDM bounds whereas $\phi_A$ is almost unconstrained. However we show that the phase of the $A$-term for top squarks is reduced due to the large top Yukawa coupling constant and aligned to that of the gaugino mass. Therefore the phase of the $A$-term for top squarks is strongly suppressed. We show that the CP asymmetry in rare $B$ decays is suppressed in the mSUGRA if the neutron and electron EDM constraints are taken into account.

In the MSSM, the Yukawa coupling constants are described by the following superpotential,

$$W_{\text{MSSM}} = (Y_U)_{ij} Q_i U_j H_2 + (Y_D)_{ij} Q_i D_j H_1 + (Y_E)_{ij} E_i L_j H_1 - \mu H_1 H_2,$$

where $Q$ and $L$ denote the $SU(2)_L$ quark and lepton doublets, $U$, $D$, and $E$ are $SU(2)_L$ singlets, and $H_1$, $H_2$ are $SU(2)_L$ Higgs doublets. The $i, j$ represent generation indices. In addition to the SUSY invariant terms, there are following soft SUSY breaking terms,

$$- \mathcal{L}_{\text{soft}} = (m_Q^2)_{ij} \tilde{q}_i^\dagger \tilde{q}_j + (m_U^2)_{ij} \tilde{u}_R^* \tilde{u}_R^* + (m_D^2)_{ij} \tilde{d}_R^* \tilde{d}_R^*$$

$$+ (m_L^2)_{ij} \tilde{\ell}_L^* \tilde{\ell}_L^* + (m_E^2)_{ij} \tilde{\ell}_L^* \tilde{\ell}_L^*$$

$$+ \Delta_1^2 h_1^* h_1 + \Delta_2^2 h_2^* h_2 + (B \mu h_1 h_2 + \text{H.c.})$$

$$+ \left[ (A_U)_{ij} \tilde{q}_L^* \tilde{h}_2 + (A_D)_{ij} \tilde{q}_L^* \tilde{h}_1 + (A_E)_{ij} \tilde{q}_L^* \tilde{h}_1 + \text{H.c.} \right]$$

$$+ \left[ \frac{1}{2} M_1 \tilde{B} \tilde{B} + \frac{1}{2} M_2 \tilde{W} \tilde{W} + \frac{1}{2} M_3 \tilde{G} \tilde{G} + \text{H.c.} \right].$$

Hereafter we denote the superpartners by small letters with tilde. The SUSY breaking terms depend on details of SUSY breaking mechanism. In the minimal supergravity model these SUSY breaking terms are originated from the gravitational interaction and given by the following universal structure at the high energy scale:

$$M_1 = M_2 = M_3 = M_X.$$
\begin{equation}
(m_Q^2)_{ij} = (m_T^2)_{ij} = (m_D^2)_{ij} = (m_U^2)_{ij} = (m_E^2)_{ij} = m_0^2 \delta_{ij},
\end{equation}
\begin{equation}
\Delta_1^2 = \Delta_2^2 = m_0^2,
\end{equation}
\begin{equation}
(A_U)_{ij} = A_X (Y_U)_{ij}, \ (A_D)_{ij} = A_X (Y_D)_{ij}, \ (A_E)_{ij} = A_X (Y_E)_{ij}.
\end{equation}

For simplicity we assume the GUT relation for gaugino masses and put the universal condition at the GUT scale ($\simeq 2 \times 10^{16}$) neglecting the renormalization effect from the Planck scale to the GUT scale. The SUSY breaking parameters at the electroweak scale are obtained by solving the RGEs. In principle, the parameters, $M_X$, $A_X$, $\mu$, and $B\mu$, can have phases. Since only two combinations of the four phases are physical CP violating phases, we take only $A_X$ and $\mu$ as complex parameters hereafter.

In order to see qualitative feature of RGEs for $A$-terms let us first neglect flavor mixings in the RGEs. The RGEs of $A$-terms for the first and second generations are given by
\begin{equation}
\frac{d}{dt} A_{e_i} = 3 \alpha_2 M_2 + 3 \alpha_1 M_1 - \alpha_f A_f - 3 \alpha_b A_b,
\end{equation}
\begin{equation}
\frac{d}{dt} A_{d_i} = \frac{16}{3} \alpha_3 M_3 + 3 \alpha_2 M_2 + \frac{7}{9} \alpha_1 M_1 - \alpha_f A_f - 3 \alpha_b A_b,
\end{equation}
\begin{equation}
\frac{d}{dt} A_{u_i} = \frac{16}{3} \alpha_3 M_3 + 3 \alpha_2 M_2 + \frac{13}{9} \alpha_1 M_1 - 3 \alpha_t A_t,
\end{equation}
where $i = 1, 2$ and for the third generation
\begin{equation}
\frac{d}{dt} A_{\tau} = 3 \alpha_2 M_2 + 3 \alpha_1 M_1 - 4 \alpha_f A_f - 3 \alpha_b A_b,
\end{equation}
\begin{equation}
\frac{d}{dt} A_b = \frac{16}{3} \alpha_3 M_3 + 3 \alpha_2 M_2 + \frac{7}{9} \alpha_1 M_1 - \alpha_f A_f - 6 \alpha_b A_b - \alpha_t A_t,
\end{equation}
\begin{equation}
\frac{d}{dt} A_t = \frac{16}{3} \alpha_3 M_3 + 3 \alpha_2 M_2 + \frac{13}{9} \alpha_1 M_1 - \alpha_b A_b - 6 \alpha_t A_t.
\end{equation}
Here $A_{f_i} \equiv (A_f)_{ii}/(Y_f)_{ii}$, $t = - \ln (Q^2)/(4\pi)$ where $Q$ is a renormalization point, $\alpha_i = g_i^2/(4\pi)$, and $\alpha_{f_i} = Y_{f_i}^2/(4\pi)$. In the right-hand sides (RHS’s) of above equations, only the Yukawa coupling constants of the third generation are retained. Since the RHS’s of RGEs for $A$-terms depend linearly on the $A$-terms and gaugino masses,
general solutions can be written in terms of the universal $A$-term and gaugino mass as follows:

$$A_{f_i} = C^A_{f_i} A_X - C^g_{f_i} M_X,$$

where the coefficients $C^A_{f_i}$ and $C^g_{f_i}$ are functions of the Yukawa and gauge coupling constants. In Fig. 1, $C^g_{f_i}$ and $C^A_{f_i}$ are shown as a function of $\tan \beta (= v_2/v_1)$. $C^A_t$ is much smaller than $C^g$ because $C^A_t$ is reduced by the large top Yukawa coupling constant. Therefore, the phase of $A$-term for top squarks is strongly suppressed due to the renormalization effects even if the phase of $A$-term at $M_X$ scale is maximal.

Considering the current experimental lower bound on the chargino mass, $m_{\tilde{\chi}^+} > 91$ GeV [11], $M_X$ at the GUT scale must be roughly larger than 120 GeV. In principle, the contribution from $A_X$ can dominate in Eq. (13) if $A_X$ is larger than $O(10)$ TeV. However, it makes scalar particles heavier than 1 TeV, in which case SUSY loop effects on FCNC processes in $B$ decays are small. As $\tan \beta$ becomes larger, $C^A_{f_i}$ for the bottom squark is reduced due to the bottom Yukawa coupling constant. Note that the suppression of the phase of $A_t$ is a general feature in models where the $A$-terms are generated at a high energy scale.

Let us discuss phenomenological consequences of SUSY CP phases on the $B \to X_s \gamma$ and $B \to X_s l^+ l^-$ decays. These processes are described by the following effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(Q) O_i(Q).$$

The operators, $O_7 - O_{10}$, are most relevant for the calculation of the processes, which are given by,

$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu},$$

$$O_8 = \frac{g_3}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} T^a b_R F^a_{\mu\nu},$$

$$O_9 = \frac{e^2}{16\pi^2} \bar{s}_L \gamma_\mu b_L \bar{l} \gamma^\mu l,$$

$$O_{10} = \frac{e^2}{16\pi^2} \bar{s}_L \gamma_\mu b_L \bar{l} \gamma^\mu \gamma_5 l.$$
In order to calculate the $B \to X_s \gamma$ and $B \to X_s l^+ l^-$ processes in the mSUGRA, we first solve the RGEs of the MSSM to determine the masses and mixings of SUSY particles. Then, integrating out SUSY particles at the electroweak scale, the SUSY contributions are included into the Wilson coefficients $C_i$ in matching conditions. The Wilson coefficients at the bottom mass scale are calculated by solving the RGE of QCD at the next-to-leading order (NLO). As for the NLO calculation we follow the results in Ref. [8, 12] for the $B \to X_s \gamma$ process, and the results in Ref. [13] for $B \to X_s l^+ l^-$ process.

The direct CP asymmetry in the $B \to X_s \gamma$ decay is given by

$$A_{CP}(\delta) = \frac{\Gamma(B \to X_s \gamma) - \Gamma(B \to X_s \gamma^*)}{\Gamma(B \to X_s \gamma) + \Gamma(B \to X_s \gamma^*)},$$

$$= \frac{\alpha_3(\mu_b)}{|C_7|^2} \left[ \frac{40}{81} \text{Im}(C_2 C_7^*) - \frac{8z}{9} [v(z) + b(z, \delta)] \text{Im} [(1 + \epsilon_s) C_2 C_7^*] \right.$$  
$$\left. - \frac{4}{9} \text{Im}(C_8 C_7^*) + \frac{8z}{27} b(z, \delta) \text{Im} [(1 + \epsilon_s) C_2 C_8^*] \right],$$

(19)

where $\delta$ is an energy cutoff parameter for the photon, $\mu_b$ is a renormalization point at the bottom mass scale, $z = (m_c/m_b)^2$, $\epsilon_s = V_{ub} V_{us}^*/(V_{tb} V_{ts}^*)$, and functions $v$ and $b$ are found in Ref. [8]. In the SM, the CP asymmetry is estimated as $A_{CP}^{SM}(\delta = 0.99) \approx 1.5 \times 10^{-2} \eta$ where $\eta$ is the Wolfenstein parameter. The SM prediction is small because the small parameter $\epsilon_s$, which is $O(10^{-2})$, is the only source of the direct CP violation in the $B \to X_s \gamma$ process. If $C_7$ or $C_8$ has a sizable new CP violating phase, $A_{CP}$ could be large.

The dilepton spectrum of the $B \to X_s l^+ l^-$ decay can be written by

$$\frac{dB(B \to X_s l^+ l^-)}{d\hat{s}} = B(B \to X_s l\bar{l}) \frac{\alpha^2}{4\pi^2} \left| \frac{V_{tb} V_{ts}^*}{V_{cb}} \right|^2 \frac{1}{f(m_c/m_b) \kappa(m_c/m_b)(1 - \hat{s})^2}$$

$$\times \left[ (|C_9^{eff}|^2 + |C_{10}^{eff}|^2)(1 + 2\hat{s}) + \frac{4}{\hat{s}} |C_7|^2(2 + \hat{s}) + 12 Re(C_7^{eff}C_9^{eff}) \right],$$

(20)

where $\hat{s}$ is the dilepton invariant mass square normalized by bottom mass square, $f = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$, and $\kappa$ is a QCD correction factor [13]. Since there is an interference term between $C_7$ and $C_9^{eff}$, the dilepton spectrum depends on the phases of $C_7$ or $C_9^{eff}$.
For numerical calculations in the mSUGRA, we scanned the SUSY parameters in the range $0 < m_0 < 1$ TeV, $0 < M_X < 0.5$ TeV, $|A_X| < 5m_0$, and we follow Ref. [7] for detailed procedures of the calculation. For definiteness, we take the KM parameters, $|V_{us}| = 0.2196$, $|V_{cb}| = 0.0395$, $|V_{ub}/V_{cb}| = 0.08$, and $\delta_{13} = \pi/2$ in the standard parametrization [14]. As for the $B \to X_s\gamma$ decay, we take $\delta = 0.99$, $\mu_b = m_b = 4.8$ GeV, and $m_t = 175$ GeV.

In Fig. 2 the neutron EDM is shown as a function of $\phi_\mu$ and $\phi_A$ for $\tan \beta = 30$. In the numerical calculation only the neutron EDM from the quark EDM Ms is included. Recently it was pointed out that the EDM constraints may be relaxed by a cancellation among different contributions in the mSUGRA [4, 5]. However, we do not rely on such a cancellation because each contribution has different hadronic uncertainty, so that it is difficult to determine the parameters where such a cancellation occurs. We are only interested in the case where SUSY particles are lighter than 1 TeV because otherwise SUSY effects on the $B \to X_s\gamma$ and $B \to X_sl^+l^-$ decays are strongly suppressed. In such a case, as pointed out in Ref. [4], the neutron EDM exceeds the present experimental bound, $|d_n| \leq 0.97 \times 10^{-25}$ e cm [15], unless $\phi_\mu$ is $\lesssim 10^{-2}$. On the other hand, $\phi_A$ can be $O(1)$ even if the masses of SUSY particles are $O(100)$ GeV.

The real and imaginary parts of $C_7$ at the bottom mass scale divided by the SM value are plotted in Fig. 3 for $\tan \beta = 3, 10, 30$. As in the case of no SUSY CP violating phase, the SUSY contributions to $C_7$ and $C_8$ become large, however, those to $C_9$ and $C_{10}$ are small. In this figure, the experimental bound on the $B \to X_s\gamma$ branching ratio, $2.0 \times 10^{-4} < B(B \to X_s\gamma) < 4.5 \times 10^{-4}$ [16], is imposed, therefore the region between two circles are allowed. It is interesting to see that without the neutron and electron EDM constraints, $C_7$ can have different phase from the SM value. On the other hand, with the EDM constraints, i.e., $|d_n| < 0.97 \times 10^{-25}$ e cm, $|d_e| < 4.0 \times 10^{-27}$ e cm [17], the imaginary part of $C_7/C_7^{SM}$ is quite suppressed, and either $C_7 \simeq C_7^{SM}$ or $C_7 \simeq -C_7^{SM}$ region is allowed. This is a similar result to that obtained without the SUSY CP violating phases [7]. It is known that the charged Higgs boson and the chargino contributions to $C_7$ can be significant, and that the charged Higgs boson contribution to $C_7$ has the same phase as the SM contribution. On the other hand the chargino-stop loop contribution to $C_7$ depends on the new SUSY CP phases. In order to have the large phase of $C_7$, the imaginary
part of the chargino contribution must be large. With the neutron and electron EDM constraints, however, $\phi_\mu$ must be quite small. Moreover the phase of $A_t$ is also suppressed due to the RGE effect as discussed above. Therefore it is difficult to have large phase of $C_7$. We also find that $C_8/C_8^{SM}$ does not induce large imaginary part although the magnitude itself can be changed by the SUSY contributions. This means that large CP violating phases do not appear in rare $B$ decays in the framework of the mSUGRA even if the new CP violating phases are introduced. This is a distinct feature from the result which is obtained in Ref. \[10\] where the authors did not follow the universality condition for scalar masses at the GUT scale. From Fig. 3(a)-(c), only for $\tan \beta = 30$, there is parameter space where $C_7/C_7^{SM}$ is negative. We find that in this parameter region the lighter stop mass is less than about 200 GeV as in the case of no new SUSY CP phase [7].

In Fig. 4(a)-(b), we plot the $B \to X_s \mu^+\mu^-$ branching ratio and the direct CP asymmetry in the $B \to X_s \gamma$ versus the neutron EDM for $\tan \beta = 30$. After taking into account the neutron and electron EDM constraints, we show that there are two branches of the $B \to X_s \mu^+\mu^-$ branching ratio and the larger branching ratio corresponds to the case where the sign of $C_7$ is opposite to that in the SM. The branching ratio can be about twice as large as that in the SM with $C_7 \simeq -C_7^{SM}$. The CP asymmetry turns out to be less than 2%.

In conclusion, we investigate the effect of the SUSY CP violating phases $(\phi_\mu, \phi_A)$ on the rare $B$ decays in the mSUGRA model taking into account the RGEs for the SUSY breaking parameters. If the SUSY particles are in the hundred GeV region, $\phi_\mu$ is strongly constrained by the EDM bounds. On the other hand, the phase of $A$-term for top squarks is aligned to that of the gaugino masses due to the RGEs. As a consequence, the effect of the SUSY CP violating phases is small and either $C_7 \simeq C_7^{SM}$ or $C_7 \simeq -C_7^{SM}$ is allowed. We show that the direct CP asymmetry is less than 2% taking into account the EDM constraints. For the $B \to X_s l^+l^-$ decay, there is a twofold ambiguity of the branching ratio according to the sign of $C_7$. The branching ratio can be twice as large as the SM value when $C_7 \simeq -C_7^{SM}$.

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Figure Captions

FIG. 1 The coefficients $C^A$ and $C^g$ in Eq. (13) are shown as a function of $\tan \beta$. Here we take $\overline{MS}$ masses for quarks as $m_u = 3.3$ MeV, $m_d = 6.0$ MeV, and $m_s = 120$ MeV at the scale of 2 GeV. We take pole masses as $m_c = 1.4$ GeV and $m_b = 4.8$ GeV, $m_t = 175$ GeV.

FIG. 2 The absolute value of the neutron EDM ($|d_n|$) is plotted as a function of $\phi_\mu$ (a) and $\phi_A$ (b) for $\tan \beta = 30$. Here input SUSY parameters are scanned in a region, $0 < m_0 < 1$ TeV, $0 < M_X < 0.5$ TeV, and $|A_X| < 5m_0$. The dashed line represents the present experimental upper bound, $|d_n| < 0.97 \times 10^{-25}$ e cm. For Fig. 2(b), squares correspond to the parameter spaces $\phi_\mu = 0, \pi$.

FIG. 3 $C_7^g/C_7^{SM}$ at the bottom mass scale is shown imposing the current experimental bound for the $B \rightarrow X_s \gamma$ branching ratio for $\tan \beta = 3$ (a), 10 (b), 30 (c). Dots correspond to values without the neutron and electron EDM constraints and squares correspond to values with the EDM constraints. The input SUSY parameters are the same as Fig. 2.

FIG. 4 (a). The $B \rightarrow X_s \mu^+\mu^-$ branching ratio is plotted as a function of the neutron EDM. As for the $B \rightarrow X_s \mu^+\mu^-$ branching ratio, in order to avoid the $J/\psi$ resonance, we integrate the dilepton spectrum in a region $4m_\mu^2 < s < (m_{J/\psi} - 0.1(\text{GeV}))^2$ where $s$ is the dilepton invariant mass square. (b). The absolute value of the direct CP asymmetry in the $B \rightarrow X_s \gamma$ ($|A_{CP}|$) is plotted as a function of the neutron EDM. In these figures the input SUSY parameters are the same as Fig. 2. The dashed line represents the present upper bound for the neutron EDM. Squares correspond to the parameter spaces with the electron and neutron EDM constraints.
Fig. 1
Fig. 2(a)
Fig. 2(b)
Fig. 3(a)

\[ \text{Im}(C_7 / C_7^{SM}) \]

\[ \text{Re}(C_7 / C_7^{SM}) \]

- all
- w/ EDM

\[ \tan \beta = 3 \]
Fig. 3(b)
Fig. 3(c)
Fig. 4(a)
Fig. 4(b)