Exploring flavor structure of supersymmetry breaking from rare B decays and the unitarity triangle

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We study effects of supersymmetric particles in various rare B decay processes as well as in the unitarity triangle analysis. We consider three different supersymmetric models, the minimal supergravity, $SU(5)$ SUSY GUT with right-handed neutrinos, and the minimal supersymmetric standard model with $U(2)$ flavor symmetry. In the $SU(5)$ SUSY GUT with right-handed neutrinos, we consider two cases of the mass matrix of the right-handed neutrinos. We calculate direct and mixing-induced CP asymmetries in the $b \to s\gamma$ decay and CP asymmetry in $B_d \to \phi K_S$ as well as the B_s–$\overline{B}_s$ mixing amplitude for the unitarity triangle analysis in these models. We show that large deviations are possible for the $SU(5)$ SUSY GUT and the $U(2)$ model. The patterns and correlations of deviations from the standard model will be useful to discriminate the different SUSY models in future B experiments.

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I. INTRODUCTION

Success of B factory experiments at KEK and SLAC indicates that B physics is important to explore origins of the flavor mixing and the CP violation in the quark sector. The CP asymmetry in the $B_d \to J/\psi K_S$ mode is precisely determined, and a CP violation parameter $\sin 2\phi_1$ (or $\sin 2\beta$) is found to be consistent with the prediction in the standard model (SM) [1]. In addition, branching ratios and CP asymmetries in various rare B decays have been reported. In future, we expect much improvement in measurements of CP violation and rare B decays at e^+e^- B factories as well as hadron B experiments [2].

Goals of future B physics are not only to very precisely determine the parameters of the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements [3], but also to search for new sources of CP violation and flavor mixings. For instance, scalar quark (squark) mass matrices could be such new sources in supersymmetric models. Since the flavor structure of the squark mass matrices depends on the mechanism of supersymmetry (SUSY) breaking at a higher energy scale and interactions above the weak scale through the renormalization, future B physics can provide quite important information on the origin of SUSY breaking.

In our previous papers [4,5], we studied the flavor signals in three different models, namely, the minimal supergravity (mSUGRA), the $SU(5)$ SUSY GUT grand unified theory (GUT) with right-handed neutrinos, and the minimal supersymmetric standard model (MSSM) with $U(2)$ flavor symmetry [6,7]. These models are typical solutions of the SUSY flavor problem. They have different flavor structures in the squark mass matrices at the electroweak scale. Thus, they may be distinguished by low-energy quark flavor signals. We calculated SUSY contributions to the B_d–$\overline{B}_d$, B_s–$\overline{B}_s$, and K^0–$\overline{K}^0$ mixings in these models, and showed that the consistency test of the unitarity triangle from angle and length measurements are useful to discriminate these models.

In addition to the consistency test of the unitarity triangle, there are several promising ways to search for new physics effects through B decay processes. As pointed out in the context of SUSY models [8,9], comparison of time-dependent CP asymmetries in $B_d \to J/\psi K_S$, $B_d \to \phi K_S$, and $B_d \to \eta' K_S$ provides us with information on new CP phases in the $b \to s$ transition, because these asymmetries are expected to be the same in the SM. Recent results on the CP asymmetry in $B_d \to \phi K_S$ by Belle and BaBar collaborations indicate a 2.7σ deviation from the SM prediction [10]. This anomaly may be attributed to new physics, SUSY with R parity [11,12], SUSY without R parity [13], or other models [14]. Moreover, the CP asymmetries in the $b \to s\gamma$ process [15,16] have been extensively studied in several models, and they would exhibit substantial deviation from the SM in some models [17]. The branching ratio and decay distributions of $b \to s l \overline{l}$ have also examined by several authors in different contexts of new physics, and they may probe different aspects of new physics [18,19].

In this paper, we extend our previous analysis [4] to rare B decay processes, especially $b \to s$ transitions. We investigate the direct CP asymmetry in $b \to s\gamma$, and the mixing-induced CP violation in $B_d \to M_s \gamma$ process, where M_s is a CP eigenstate hadron with strangeness, and CP asymmetry in $B_d \to \phi K_S$ process. We show that the above three models exhibit different patterns of deviation from the SM. These observables as well as those studied in our previous paper [4]

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could play an important role in a new physics search at future B experiments, such as a super B factory [20] and hadron B experiments [2].

The strategy of the present work and [4] is different from most other works. For each model of SUSY, we calculate SUSY effects in various mixings (B_d–$\overline{B}_d$, B_s–$\overline{B}_s$, and K^0–$\overline{K}^0$) and rare decay processes, and identify possible patterns of deviations from the SM predictions. We then compare patterns of the new physics signals for different models. In this way we may be able to distinguish different models of SUSY breaking scenarios, or at least obtain important clues to identity the SUSY breaking sector. Most of past works deal with a specific observable signal in a particular SUSY model. The strategy of combining various information in B physics will be important in future, especially in the days of a super B factory and dedicated hadron B experiments. The purpose of the present work is to demonstrate how such global analysis in B physics is useful to explore the flavor structure of SUSY breaking sectors.

In the present work, some of our calculations are a reanalysis of past works under most updated phenomenological constraints, and others are new studies. Even in the case that a similar calculation can be found in the literature for a specific process and a model, we repeat the calculation in order to treat various processes in a uniform way. In the mSUGRA model, B_d–$\overline{B}_d$, B_s–$\overline{B}_s$, and K^0–$\overline{K}^0$ mixing, and the direct CP violation of $b\to s\gamma$ were studied previously. Although the mixing-induced CP violation in $B_d\to M_s\gamma$ process and CP asymmetry in $B_d\to\phi K_S$ process have not explicitly considered before, it was recognized that such processes did not induce interesting signals once the severe constraints from various electric dipole moments were applied. We have confirmed this by explicit calculations. For the $SU(5)$ SUSY GUT with right-handed neutrinos, we have found that flavor signals are quite different for different choices of the heavy right-handed neutrino mass matrix. The "degenerate case" defined in Sec. II was considered in [4,21,22]. In particular, SUSY effects on the mixing amplitudes were studied in [21,22], and the mixing-induced CP violation in $B_d\to M_s\gamma$ process was also considered in [21]. The direct CP violation in $b\to s\gamma$ and the CP asymmetry in $B_d\to\phi K_S$ process are analyzed here for the first time. The analysis of B physics signals in "nondegenerate case" is new. We compare the implications of a consistency test of the unitarity triangle for degenerate and nondegenerate cases, which has been done only for degenerate case in [4]. We also present analysis of rare decay processes and the B_s mixing for the nondegenerate case, which partly overlaps with a recent work in [12]. For the $U(2)$ model, flavor signals has been considered previously for mixing amplitudes in [4,24], but a quantitative analysis of various rare decay modes has not yet appeared in the literature. Preliminary results of our analysis are presented in a workshop report [5], but the nondegenerate case is not included in Ref. [5].

Although we tried to clarify a characteristic feature of each model, this cannot be complete because of large numbers of free parameters. There might be some parameter space where new contributions, which are not shared in a generic parameter space, become particularly important. For example, it was pointed out recently that neutral Higgs-boson exchange effects may contribute to the various flavor-changing process, especially for a large value of the ratio of the two-vacuum expectation values ($\tan\beta$) [23], but we do not take into account these effects. Although we estimate that such an effect is small for the parameter region presented numerically in this paper, this effect will be potentially important.

This paper is organized as follows. In Sec. II, we introduce the three models. The B_d–$\overline{B}_d$ mixing, the B_s–$\overline{B}_s$ mixing, CP asymmetries in $b\to s\gamma$ and $B_d\to\phi K_S$ are discussed in Sec. III. The numerical results on these observables are presented in Sec. IV. Our conclusion is given in Sec. V.

II. MODELS

In this section, we give a brief review of the models. They are well-motivated examples of SUSY models, and are chosen as representatives that have distinct flavor structures. A detailed description of these models can be found in Ref. [4].

A. The minimal supergravity model

In the mSUGRA, SUSY is spontaneously broken in the hidden sector and our MSSM sector is only connected to the hidden sector by the gravitation. The soft breaking terms are induced through the gravitational interaction and have no new flavor mixing at the scale where they are induced.

The soft breaking terms are specified at the GUT scale by the universal scalar mass (m_0), the universal gaugino mass ($M_{1/2}$), and the universal trilinear coupling (A_0). The soft breaking terms at the electroweak scale are determined by solving renormalization group equations.

In this model, the only source of flavor mixings is the CKM matrix. New flavor mixings at the electroweak scale come from the CKM matrix through radiative corrections.

As for CP violation, in addition to the CP phase in the CKM matrix, we have two new CP phases. One is the complex phase of the μ term (ϕ_μ), and another is the phase of A_0 (ϕ_A). Since the potential sensitivity of the neutron electric dipole moment (EDM) to CP violations in low energy SUSY models was stressed by Ellis *et al.* in Ref. [25], the neutron EDM and the electron EDM have been studied in detail by several authors in different context of low-energy SUSY [25–27]. The bottom line in the mSUGRA is that ϕ_μ and ϕ_A contribute to the neutron and the electron EDMs, and experimental constraints [28,29] on these phases are very severe. Taking these EDM constraints into account, effects of new CP phases on K and B physics have turned out to be small [30].

B. The $SU(5)$ SUSY GUT with right-handed neutrinos

In the last decade, three gauge coupling constants were determined precisely at LEP and other experiments, and the measured values turned out to be consistent with the prediction of supersymmetric grand unification. Furthermore, recent developments of neutrino experiments established the existence of small finite masses of neutrinos [31–33], which can be naturally accommodated by the seesaw model [34]. Guided by these observations, we consider $SU(5)$ SUSY GUT with right-handed neutrinos.

In this model, the soft breaking terms are the same as in the mSUGRA model at the scale where the soft breaking terms are induced. Unlike the mSUGRA model, the $SU(5)$ SUSY GUT with right-handed neutrinos has new sources of flavor mixing in the neutrino sector. A large flavor mixing in the neutrino sector can affect the right-handed down-type squark sector through GUT interactions. Quark flavor signals in this model have been studied in Refs. [9,12,21,22,35].

In the seesaw model, the neutrino mass matrix is written as

$$(m_\nu)^{ij}=\langle h_2\rangle^2 (y_\nu)^{ki}(M_N^{-1})^{kl}(y_\nu)^{lj}, \tag{1}$$

where y_ν is the neutrino Yukawa coupling constant matrix, M_N is the mass matrix of right-handed neutrinos, $\langle h_2\rangle$ denotes the vacuum expectation value of one of the Higgs fields h_2, and i,j,k,l are generation indices. In the basis that the charged lepton Yukawa-coupling constant matrix is diagonal, this neutrino mass matrix is related to the observable neutrino mass eigenvalues and the Maki-Nakagawa-Sakata (MNS) matrix [36] as

$$(m_\nu)^{ij}=(V^*_{\rm MNS})^{ik} m_\nu^k (V^\dagger_{\rm MNS})^{kj}. \tag{2}$$

In this model, the scalar lepton (slepton) masses and the A terms have the mSUGRA type structure at the Planck scale ($M_{\rm P}$) as

$$(m_L^2)^{ij}=m_0^2\delta^{ij}, \quad (m_E^2)^{ij}=m_0^2\delta^{ij}, \quad (A_E)^{ij}=m_0A_0y_e^i\delta^{ij}, \tag{3}$$

where m_L^2 and m_E^2 are the mass squared matrices of sleptons and A_E denotes the slepton trilinear scalar couplings. However, at the scale M_R, where the right-handed Majorana neutrinos are decoupled, new flavor mixings are generated by the renormalization group effects [37]. In the leading logarithmic approximation, they are given as

$$(m_L^2)^{ij}\simeq -\frac{1}{8\pi^2}m_0^2(3+|A_0|^2)(y_\nu^\dagger y_\nu)^{ij}\ln\frac{M_{\rm P}}{M_R}, \tag{4a}$$

$$(m_E^2)^{ij}\simeq 0, \tag{4b}$$

$$(A_E)^{ij}\simeq -\frac{3}{8\pi^2}m_0A_0y_e^i(y_\nu^\dagger y_\nu)^{ij}\ln\frac{M_{\rm P}}{M_R}, \tag{4c}$$

for $i\neq j$. Consequences of these mixings on lepton flavor violating processes have been investigated from various aspects [38,39]. We see that, in this model, lepton flavor-violating processes, such as $\mu\to e\gamma$, are sensitive to the off-diagonal elements of $y_\nu^\dagger y_\nu$.

We consider two cases in the $SU(5)$ SUSY GUT with right-handed neutrinos in regard to the spectrum of the right-handed Majorana neutrinos. One is the case that all the masses of heavy Majorana neutrinos are the same (degenerate case). In this simplest case, the flavor mixing of the neutrino sector is only caused by y_ν because there is no flavor mixing in M_N. Since the large mixing in the MNS matrix implies that the off-diagonal elements of y_ν are large, the $\mu\to e\gamma$ branching ratio is enhanced in the wide region of the parameter space and exceeds the experimental bound in some parameter regions. In order to suppress the $\mu\to e\gamma$ branching ratio, we consider an elaborated case that M_N is not proportional to the unit matrix (nondegenerate case). In this case, the neutrino mixing comes from both y_ν and M_N. If the large mixing in the MNS matrix originates from M_N, the corresponding off-diagonal element of y_ν need not be large. Thus, the $\mu\to e\gamma$ decay rate can be suppressed in this case.

We have new CP phases in this model. They are classified in the following three classes:

(i) The CP phases in the mSUGRA, i.e., ϕ_μ and ϕ_A.

(ii) CP phases in the neutrino sector. There are six physical complex phases in y_ν and M_N in the basis in which the charged lepton mass matrix is real and diagonal. From the combination of these six CP phases, we obtain three CP phases in the low energy region, i.e., one Dirac CP phase and two Majorana CP phases.

(iii) GUT CP phases [9,22,40]. The quark and lepton superfields are embedded in **10** and $\overline{\mathbf{5}}$ representations of $SU(5)$ as

$$\mathbf{10}_i=\{Q_i, e^{-i\phi_i^Q}(V^\dagger\overline{U})_i, e^{i\phi_i^L}\overline{E}_i\}, \quad \overline{\mathbf{5}}_i=\{\overline{D}_i, e^{-i\phi_i^L}L_i\}, \tag{5}$$

where V is the CKM matrix at the GUT scale, $Q_i(\mathbf{3},\mathbf{2},1/6)$, $\overline{U}_i(\overline{\mathbf{3}},\mathbf{1},-2/3)$, $\overline{D}_i(\overline{\mathbf{3}},\mathbf{1},1/3)$, $L_i(\mathbf{1},\mathbf{2},-1/2)$, and $\overline{E}_i(\mathbf{1},\mathbf{1},1)$ are quark and lepton superfields in the ith generation with the $SU(3)\times SU(2)\times U(1)$ gauge quantum numbers in parentheses. The phases ϕ_i^L and ϕ_i^Q obey the constraints $\phi_1^L+\phi_2^L+\phi_3^L=0$ and $\phi_1^Q+\phi_2^Q+\phi_3^Q=0$. Before the $SU(5)$ is broken, CP phases ϕ_i^L and ϕ_i^Q have physical meanings and they may play an important role in the flavor physics through the renormalization group effect above the GUT scale.

C. A model with $U(2)$ flavor symmetry

An alternative solution of the flavor problem of SUSY is introducing some flavor symmetry. $U(2)$ flavor symmetry is one of such symmetries [6,7]. We consider the model given in Ref. [7]. In this model, the quark and lepton supermultiplets in the first and the second generations transform as doublets under the $U(2)$ flavor symmetry, and the third-generation and the Higgs supermultiplets are singlets under the $U(2)$.

In order to reproduce the correct structure of the quark Yukawa coupling matrices, we assume the following breaking pattern of the $U(2)$:

$$U(2)\to U(1)\to \mathbf{1}(\text{no symmetry}). \tag{6}$$

With this assumption, we obtain the quark Yukawa coupling matrix y_Q and the squark mass matrices m_X^2,

$$y_Q^{ij}=Y_Q\begin{pmatrix} 0 & a_Q\epsilon' & 0 \\ -a_Q\epsilon' & d_Q\epsilon & b_Q\epsilon \\ 0 & c_Q\epsilon & 1 \end{pmatrix}, \quad Q=U,D, \tag{7}$$

$$m_X^2=(m_0^X)^2\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1+r_{22}^X\epsilon^2 & r_{23}^X\epsilon \\ 0 & r_{23}^{X*}\epsilon & r_{33}^X \end{pmatrix}, \quad X=Q,U,D, \tag{8}$$

where ϵ and ϵ' are order parameters of the $U(2)$ and $U(1)$ symmetry breaking, respectively, and they satisfy $\epsilon' \ll \epsilon \ll 1$, and Y_Q, a_Q, b_Q, c_Q, d_Q, and r^X are dimensionless parameters of $\mathcal{O}(1)$. As for the squark A terms, they have the same structure as the quark Yukawa coupling matrices,

$$A_Q^{ij}=A_Q^0 Y_Q\begin{pmatrix} 0 & \tilde{a}_Q\epsilon' & 0 \\ -\tilde{a}_Q\epsilon' & \tilde{d}_Q\epsilon & \tilde{b}_Q\epsilon \\ 0 & \tilde{c}_Q\epsilon & 1 \end{pmatrix}, \quad Q=U,D. \tag{9}$$

In general, though, being of $\mathcal{O}(1)$, $\tilde{a}_Q$, $\tilde{b}_Q$, $\tilde{c}_Q$, and $\tilde{d}_Q$ take different values from the corresponding parameters in Eq. (7), and we expect no exact universality of the A terms in this model.

In the mass matrices of sfermions in this model, the degeneracy between masses of the first and the second generation is naturally realized. On the other hand, the mass of the third generation may be separated from the others. There exist flavor mixings of $\mathcal{O}(\epsilon)$ between the second and the third generations of sfermions. These are new sources of flavor mixing besides the CKM matrix.

There are several efforts to explain the observed neutrino masses and mixings in SUSY models with the $U(2)$ flavor symmetry (or its discrete relatives) [41]. However, the purpose of this paper is to illustrate typical quark, especially bottom, flavor signals in several SUSY models and to examine the possibility to distinguish them. A detailed study of neutrino masses and mixings and lepton flavor signals in models with flavor symmetry is beyond the scope of the present work. Hence, in the following analysis, we will not consider the lepton sector in the $U(2)$ model.

III. PROCESSES

The processes considered in the following are the B_d–$\overline{B}_d$ and the B_s–$\overline{B}_s$ mixings, $b\to s\gamma$, and $B\to\phi K_S$. We consider the effective Lagrangian that consists of $\Delta B=1$ terms and $\Delta B=2$ terms

$$\mathcal{L}=\mathcal{L}_{\Delta B=1}+\mathcal{L}_{\Delta B=2}, \tag{10}$$

$$\begin{aligned}\mathcal{L}_{\Delta B=1}&=C_{2L}\mathcal{O}_{2L}+C'_{2L}\mathcal{O}'_{2L}+C_{LL}\mathcal{O}_{LL}\\ &\quad+C_{LR}^{(1)}\mathcal{O}_{LR}^{(1)}+C_{LR}^{(2)}\mathcal{O}_{LR}^{(2)}+C_{TL}^{(1)}\mathcal{O}_{TL}^{(1)}\\ &\quad+C_{TL}^{(2)}\mathcal{O}_{TL}^{(2)}-C_{7L}\mathcal{O}_{7L}-C_{8L}\mathcal{O}_{8L}+(L\leftrightarrow R),\end{aligned} \tag{11}$$

where $\mathcal{O}$'s are

$$\mathcal{O}_{2L}=(\overline{s}_\alpha\gamma^\mu c_{L\alpha})(\overline{c}_\beta\gamma^\mu b_{L\beta}), \tag{12a}$$

$$\begin{aligned}\mathcal{O}'_{2L}&=(\overline{s}_\alpha\gamma^\mu u_{L\alpha})(\overline{u}_\beta\gamma^\mu b_{L\beta})\\ &\quad-(\overline{s}_\alpha\gamma^\mu c_{L\alpha})(\overline{c}_\beta\gamma^\mu b_{L\beta}),\end{aligned} \tag{12b}$$

$$\mathcal{O}_{LL}=(\overline{s}_\alpha\gamma^\mu b_{L\alpha})(\overline{s}_\beta\gamma_\mu s_{L\beta}), \tag{12c}$$

$$\mathcal{O}_{LR}^{(1)}=(\overline{s}_\alpha\gamma^\mu b_{L\alpha})(\overline{s}_\beta\gamma_\mu s_{R\beta}), \tag{12d}$$

$$\mathcal{O}_{LR}^{(2)}=(\overline{s}_\alpha\gamma^\mu b_{L\beta})(\overline{s}_\beta\gamma_\mu s_{R\alpha}), \tag{12e}$$

$$\mathcal{O}_{TL}^{(1)}=\frac{1}{4}(\overline{s}_\alpha[\gamma^\mu,\gamma^\nu]b_{L\alpha})(\overline{s}_\beta[\gamma_\mu,\gamma_\nu]s_{L\beta}), \tag{12f}$$

$$\mathcal{O}_{TL}^{(2)}=\frac{1}{4}(\overline{s}_\alpha[\gamma^\mu,\gamma^\nu]b_{L\beta})(\overline{s}_\beta[\gamma_\mu,\gamma_\nu]s_{L\alpha}), \tag{12g}$$

$$\mathcal{O}_{7L}=\frac{e}{16\pi^2}m_b\overline{s}\frac{i}{2}[\gamma^\mu,\gamma^\nu]b_R F_{\mu\nu}, \tag{12h}$$

$$\mathcal{O}_{8L}=\frac{g_3}{16\pi^2}m_b\overline{s}^\alpha\frac{i}{2}[\gamma^\mu,\gamma^\nu]T_{\alpha\beta}^{(a)}b_R^\beta G_{\mu\nu}^{(a)}. \tag{12i}$$

Among the above Wilson coefficients, C_{2L} is dominated by the tree contributions from the SM at the weak scale and the others are induced by loop effects. Therefore, one obtains $C'_{2L}=\epsilon_u C_{2L}$, where $\epsilon_u=-V_{us}^*V_{ub}/V_{ts}^*V_{tb}$. The coefficients C_{LL}, $C_{LR}^{(1)}$, and $C_{LR}^{(2)}$ are also dominated by the SM contribution because of the QCD correction below the electroweak scale. $\mathcal{L}_{\Delta B=2}$ is described in our previous paper [4].

We discussed the B_d–$\overline{B}_d$ and the B_s–$\overline{B}_s$ mass splittings Δm_{B_d} and Δm_{B_s} in Ref. [4]. In this paper, we consider both the direct and the mixing-induced CP asymmetries in $b\to s\gamma$ and the CP asymmetry in $B\to\phi K_S$ in addition to the above $\Delta B=2$ process.

About the B^0–$\overline{B}^0$ mixing processes, the mixing matrix elements $M_{12}(B_d)$ and $M_{12}(B_s)$ are defined as

$$M_{12}(B_q)=-\frac{1}{2m_{B_q}}\langle B_q|\mathcal{L}_{\Delta B=2}|\overline{B}_q\rangle, \tag{13}$$

where $q=d,s$. We can express Δm_{B_d} and Δm_{B_s} in terms of $M_{12}(B_q)$ as

$$\Delta m_{B_q}=2|M_{12}(B_q)|. \tag{14}$$

The direct CP asymmetry in the inclusive decays $B\to X_s\gamma$ is defined as [15]

$$A_{CP}^{\rm dir}(B\to X_s\gamma)=\frac{\Gamma(\overline{B}\to X_s\gamma)-\Gamma(B\to X_{\bar{s}}\gamma)}{\Gamma(\overline{B}\to X_s\gamma)+\Gamma(B\to X_{\bar{s}}\gamma)}$$

$$=-\frac{\alpha_3}{\pi(|C_{7L}|^2+|C_{7R}|^2)}\bigg[-{\rm Im}\, r_2{\rm Im}[(1-\epsilon_u)C_{2L}C_{7L}^*]+\frac{80}{81}\pi\,{\rm Im}(\epsilon_u C_{2L}C_{7L}^*)+\frac{8}{9}\pi\,{\rm Im}(C_{8L}C_{7L}^*)$$
$$-{\rm Im}\, f_{27}{\rm Im}[(1-\epsilon_u)C_{2L}C_{7L}^*]+\frac{1}{3}{\rm Im}\, f_{27}{\rm Im}[(1-\epsilon_u)C_{2L}C_{8L}^*]+(L\leftrightarrow R)\bigg], \tag{15}$$

where the functions r_2 and f_{27} are found in Ref. [42].

The time-dependent CP asymmetry in the B_d decays to a CP eigenstate f_{CP} is given by

$$\frac{\Gamma(\overline{B}_d(t)\to f_{CP})-\Gamma(B_d(t)\to f_{CP})}{\Gamma(\overline{B}_d(t)\to f_{CP})+\Gamma(B_d(t)\to f_{CP})}$$
$$=A_{CP}^{\rm dir}(B_d\to f_{CP})\cos\Delta m_{B_d}t+A_{CP}^{\rm mix}(B_d\to f_{CP})\sin\Delta m_{B_d}t. \tag{16}$$

In the $b\to s\gamma$ decays, we consider the time-dependent mixing-induced CP asymmetry in $B_d\to M_s\gamma$, where M_s denotes a hadronic CP eigenstate that includes a strange quark, such as K^* or K_1. $A_{CP}^{\rm mix}(B_d\to M_s\gamma)$ is given as [16]

$$A_{CP}^{\rm mix}(B_d\to M_s\gamma)=\frac{2\,{\rm Im}(e^{-i\phi_B}C_{7L}C_{7R})}{|C_{7L}|^2+|C_{7R}|^2}, \tag{17}$$

where

$$e^{i\phi_B}=\frac{M_{12}(B_d)}{|M_{12}(B_d)|}. \tag{18}$$

As for $B_d\to\phi K_S$, we consider $A_{CP}^{\rm mix}(B_d\to\phi K_S)$, which is given as

$$A_{CP}^{\rm mix}(B_d\to\phi K_S)=\frac{2\,{\rm Im}(e^{-i\phi_B}\overline{\mathcal{A}}\mathcal{A})}{|\mathcal{A}|^2+|\overline{\mathcal{A}}|^2}, \tag{19}$$

where $\mathcal{A}$ and $\overline{\mathcal{A}}$ are decay amplitudes of $B_d\to\phi K$ and $\overline{B}_d\to\phi\overline{K}$, respectively. Since $B_d\to\phi K_S$ is a hadronic decay mode, the calculation of the decay amplitude suffers from large theoretical uncertainties. Here we use a method based on the naive factorization. Details of the calculation of $\mathcal{A}$ is given in Refs. [9,8,43]. Using the naive factorization ansatz, we obtain

$$\overline{\mathcal{A}}\equiv-\langle\phi\overline{K}|\mathcal{L}|\overline{B}\rangle$$
$$=-H_V\bigg[\frac{1}{3}C_{LL}+\frac{1}{4}C_{LR}^{(1)}+\frac{1}{12}C_{LR}^{(2)}-\frac{7}{6}\frac{H_T}{H_V}C_{TL}^{(1)}-\frac{5}{6}\frac{H_T}{H_V}C_{TL}^{(2)}+\frac{\alpha_s}{4\pi}\frac{4}{9}\kappa_{\rm DM}C_{8L}+(L\leftrightarrow R)$$
$$+\frac{1}{9}P_G^{(c)}(q^2,m_b^2)C_{2L}+\frac{1}{9}(P_G^{(u)}(q^2,m_b^2)-P_G^{(c)}(q^2,m_b^2))\epsilon_u C_{2L}\bigg], \tag{20}$$

where $H_V=3\langle\phi\overline{K}|\mathcal{O}_{LL}|\overline{B}\rangle$ and $H_T=-(6/7)\langle\phi\overline{K}|\mathcal{O}_{TL}^{(1)}|\overline{B}\rangle$. $P_G^{(u,c)}(q^2,m_b^2)$ comes from the one-loop matrix element of $\mathcal{O}_{2L}$, q^2 is the momentum transfer of the exchanged gluon, and $\kappa_{\rm DM}$ is an $\mathcal{O}(1)$ coefficient [43] that parametrizes the matrix element of $\mathcal{O}_8$. The concrete form of $P_G^{(q_i)}(q^2,m_b^2)$ is $P_G^{(q_i)}(q^2,m_b^2)=-(\alpha_s/(4\pi))(G(m_{q_i}^2,q^2,m_b^2)+2/3)$ for the NDR scheme [44] with

$$G(m_{q_i}^2,q^2,m_b^2)=-4\int_0^1 dx\,x(1-x)$$
$$\times\ln\left(\frac{m_{q_i}^2-q^2x(1-x)}{m_b^2}\right). \tag{21}$$

In the constituent quark model, H_T/H_V is proportional to m_ϕ/m_B, and thus the contributions from $C_{TL}^{(1)}$ and $C_{TL}^{(2)}$ are neglected.

In our calculations, we take $q^2=m_b^2/2$ and $\kappa_{\rm DM}=1$. Though these approximations are difficult to be justified in QCD, we employ them for an illustration that may provides the correct order of magnitude.

IV. NUMERICAL ANALYSIS

A. Parameters

1. Parameters in the minimal supergravity model

The parameters we use in our calculation are almost the same as those used in our previous paper [4] except for CP

TABLE I. The neutrino parameters used in the nondegenerate case. We show the neutrino Yukawa coupling matrices and the mass eigenvalues of the right-handed neutrinos for $\tan\beta=5$ and $\tan\beta=30$. These Yukawa coupling matrices give the structure as given in Eq. (23)

$\tan\beta$	y_ν	eigenvalues of $M_N(\times 10^{14}$ GeV)
5	$\begin{pmatrix} 0.13 & 0 & 0 \\ 0 & 0.099 & -0.099 \\ 0 & 0.46 & 0.46 \end{pmatrix}$	4.4 0.56 1.7
30	$\begin{pmatrix} 0.13 & 0 & 0 \\ 0 & 0.098 & -0.098 \\ 0 & 0.47 & 0.47 \end{pmatrix}$	4.5 0.57 1.8

phases. In our calculation, we treat the masses and the mixing matrices in the quark and lepton sectors as input parameters that determine the Yukawa coupling matrices.

The CKM matrix elements V_{us}, V_{cb}, and $|V_{ub}|$ are determined by experiments independently of new physics because they are based on tree-level processes. We adopt $V_{us}=0.2196$ and $V_{cb}=0.04$ in the following calculations and vary $|V_{ub}|$ within a range $|V_{ub}/V_{cb}|=0.09\pm0.01$. Note that the current error of $|V_{ub}|$ is estimated to be larger than this value but we expect theoretical and experimental improvements in near future. We vary the CKM phase $\phi_3\equiv\arg(-V_{ub}^*V_{ud}/V_{cb}^*V_{cd})$ within $\pm180°$, because it is not yet constrained by tree-level processes free from new physics contributions.

As for the SUSY parameters, we take the convention that the unified gaugino mass $M_{1/2}$ is real. It is known that ϕ_μ is strongly constrained by the upper bound of EDMs, while the corresponding constraint on ϕ_A is not so tight [27]. Accordingly, we fix ϕ_μ as 0° or 180° at the electroweak scale. We vary the universal scalar mass m_0, $M_{1/2}$, and the proportional constant of A terms to Yukawa coupling matrix A_0m_0 within the ranges $0<m_0<3$TeV, $0<M_{1/2}<1$TeV, $|A_0|<5$, and $-180°<\phi_A<180°$. We take the ratio of two VEVs $\tan\beta=\langle h_2\rangle/\langle h_1\rangle=30$ or 5.

2. Parameters in the SU(5) SUSY GUT with right-handed neutrinos

In the $SU(5)$ SUSY GUT with right-handed neutrinos, we need to specify the parameters in the neutrino sector in addition to the quark Yukawa coupling constants given in the previous discussion. We take the neutrino masses as $m_{\nu_3}^2-m_{\nu_2}^2=3.5\times10^{-3}\mathrm{eV}^2$, $m_{\nu_2}^2-m_{\nu_1}^2=6.9\times10^{-5}\mathrm{eV}^2$, and $m_{\nu_1}\simeq0.001\mathrm{eV}$, and the MNS mixing matrix as

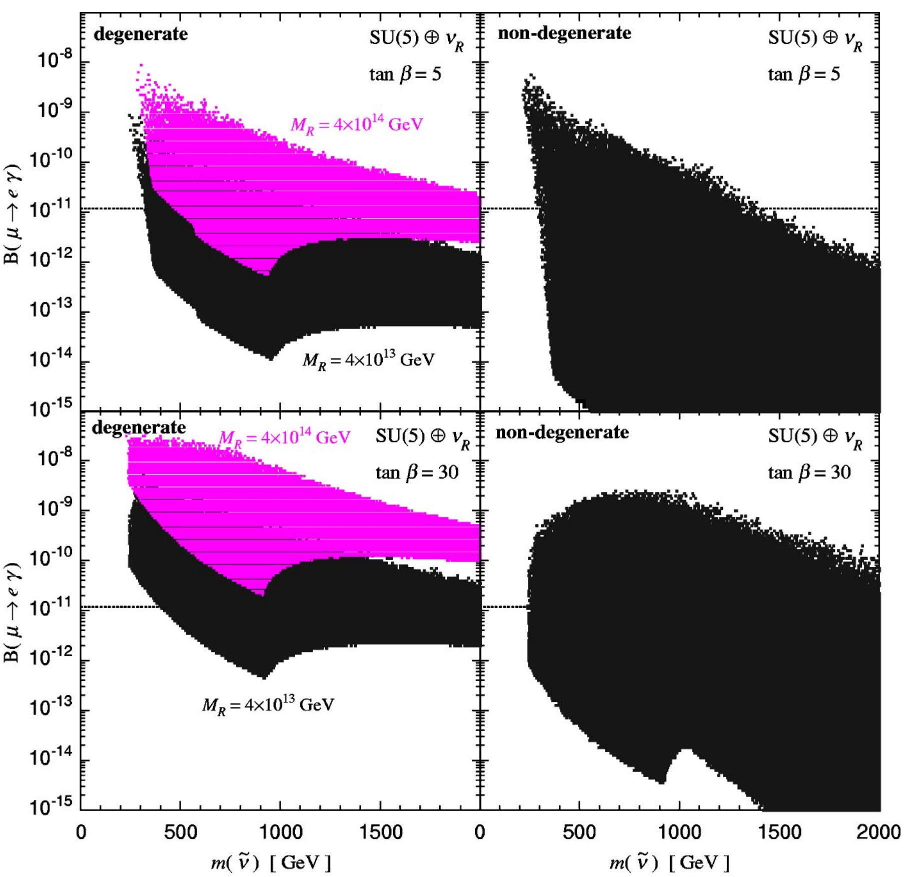

FIG. 1. The branching ratio of $\mu\rightarrow e\gamma$ as functions of the lightest sneutrino mass in the $SU(5)$ SUSY GUT with right-handed neutrinos. The dotted line shows the experimental upper bound.

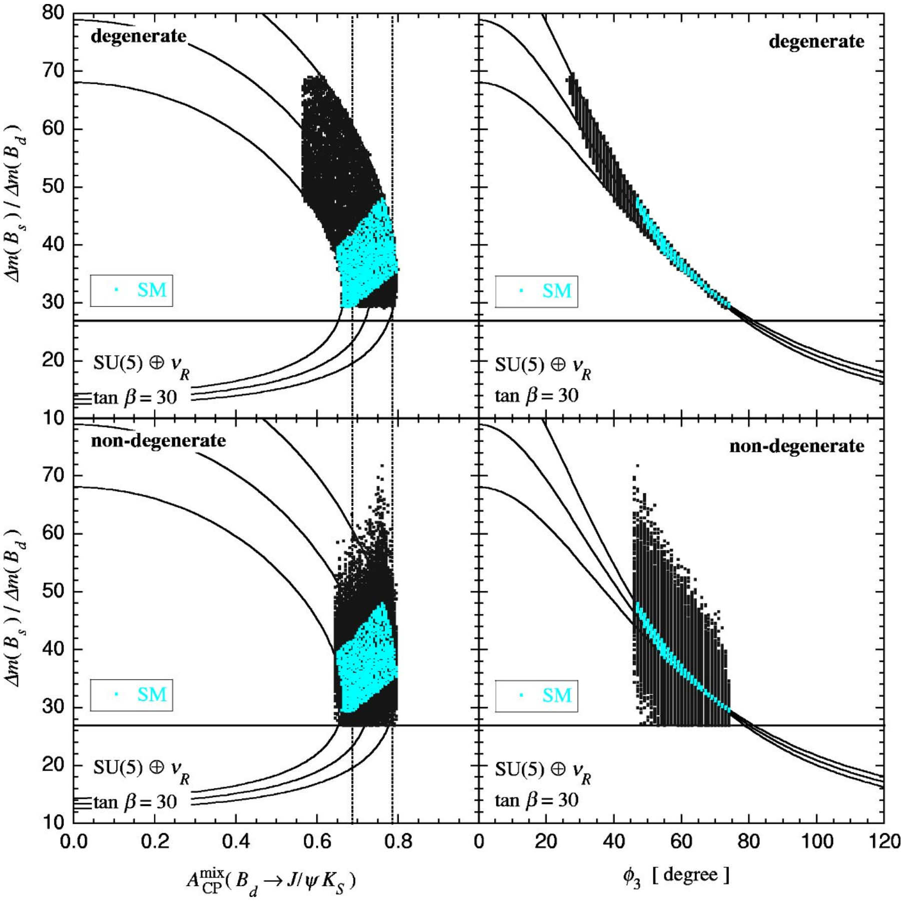

FIG. 2. $\Delta m_{B_s}/\Delta m_{B_d}$ vs. the mixing-induced CP asymmetry of $B_d \to J/\psi K_S$ and ϕ_3 in the $SU(5)$ SUSY GUT with right-handed neutrinos. The light-colored regions show the allowed region in the SM. The curves show the SM values with $|V_{ub}/V_{cb}| = 0.08$, 0.09, and 0.10. This plot corresponds to Fig. 5 of Ref. [4].

$$V_{\rm MNS} = \begin{pmatrix} c_\odot c_{13} & s_\odot c_{13} & s_{13} \\ -s_\odot c_{\rm atm} - c_\odot s_{\rm atm} s_{13} & c_\odot c_{\rm atm} - s_\odot s_{\rm atm} s_{13} & s_{\rm atm} c_{13} \\ s_\odot s_{\rm atm} - c_\odot c_{\rm atm} s_{13} & -c_\odot s_{\rm atm} - s_\odot c_{\rm atm} s_{13} & c_{\rm atm} c_{13} \end{pmatrix}, \qquad (22)$$

($c_i = \cos\theta_i, s_i = \sin\theta_i$) with $\sin^2 2\theta_{\rm atm} = 1$, $\tan^2\theta_\odot = 0.420$, and $\sin^2 2\theta_{13} = 0$. These mass squared differences and mixing angles are consistent with the observed solar and atmospheric neutrino oscillations [31], the K2K experiment [32], and the KamLAND experiment [33]. Only the upper bound of $\sin^2 2\theta_{13}$ is obtained by reactor experiments [45], and we take the above value as an illustration. We do not introduce the Dirac and Majorana CP phases in the neutrino sector for simplicity.

We consider $M_R = 4.0 \times 10^{13}$ GeV and $M_R = 4.0 \times 10^{14}$ GeV for the degenerate case. (In this case, M_R is the same as the common mass of the right-handed neutrinos.) In the nondegenerate case, we take the neutrino Yukawa coupling matrix as

$$y_\nu^\dagger y_\nu = \begin{pmatrix} Y_{11} & 0 & 0 \\ 0 & Y_{22} & Y_{23} \\ 0 & Y_{23}^* & Y_{33} \end{pmatrix} \qquad (23)$$

in order to avoid a too-large SUSY contribution in the branching ratio of $\mu \to e\gamma$. The masses and mixings of the right-handed neutrinos are determined to reproduce the observed neutrino masses and $V_{\rm MNS}$. In Table I, we show the numerical values of the neutrino parameters in the nondegenerate case. We integrate out the right-handed neutrinos at $M_R = 4.0 \times 10^{14}$ GeV in the nondegenerate case.

For the GUT phases ϕ_i^Q and ϕ_i^L, we take $\phi_i^Q = 0$ and vary ϕ_i^L within $-180° < \phi_i^L < 180°$ while $\phi_1^L + \phi_2^L + \phi_3^L = 0$ is satisfied.

The soft SUSY breaking parameters in this model are assumed to be universal at the Planck scale, and the running effect between the Planck scale and the GUT scale is taken

TABLE II. Possible deviations of ϕ_3 and $\Delta m_{B_s}/\Delta m_{B_d}$ from values expected in the SM. √ means large deviation.

		$SU(5)$ SUSY GUT		
	mSUGRA	degenerate	non-degenerate	$U(2)$
ϕ_3	-	√	-	√
$\Delta m_{B_s}/\Delta m_{B_d}$	-	√	√	√

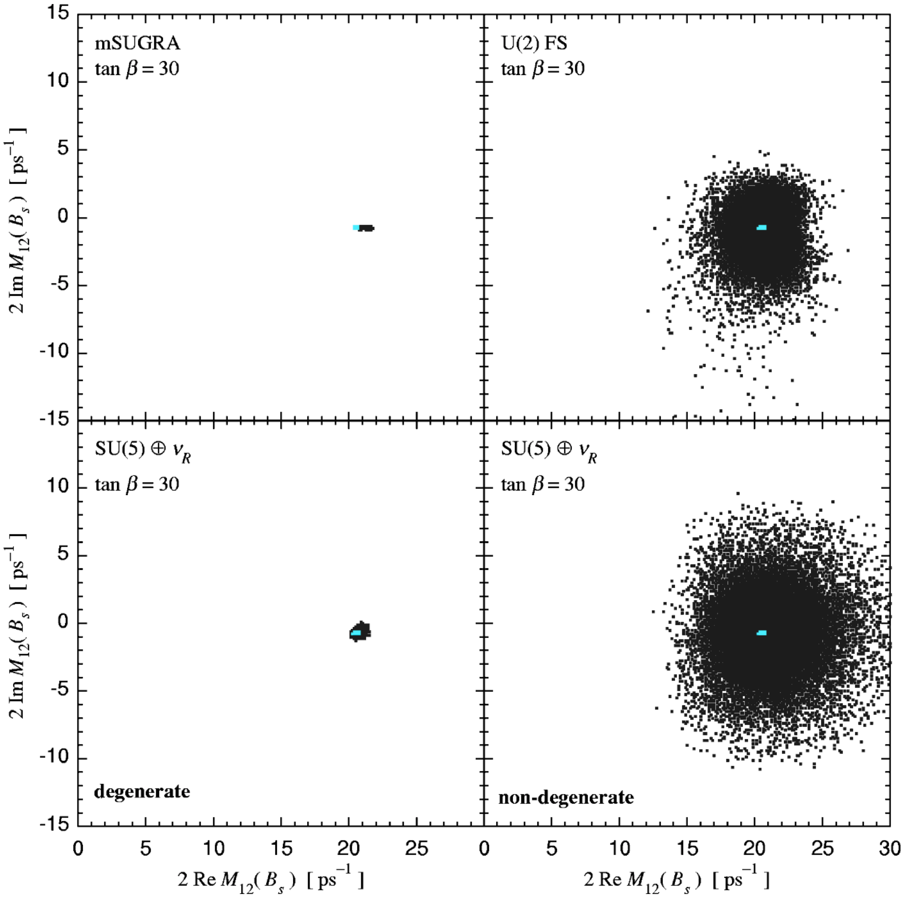

FIG. 3. Real and imaginary parts of $M_{12}(B_s)$. The SM value is shown in a light color.

into account. We scan the same ranges for m_0, $M_{1/2}$, ϕ_A, and $|A_0|$ as those in the mSUGRA case.

In Fig. 1, we show the branching ratio of $\mu\to e\gamma$ in both the degenerate and the nondegenerate cases of the $SU(5)$ SUSY GUT with right-handed neutrinos. As seen in this figure, the experimental constraint on the parameter space is stricter for the degenerate than for the nondegenerate case. Both in the degenerate and the nondegenerate cases, the SUSY contribution to $\mu\to e\gamma$ becomes larger for larger M_R [38,39]. However, the contribution is less significant in the nondegenerate case for a similar M_R [39]. In fact, for $M_R=4.0\times10^{14}$ GeV in the degenerate case, the SUSY contribution to $\mu\to e\gamma$ is so large that most of the parameter region is excluded when $\tan\beta=30$. While, in the nondegenerate case, a large part of the parameter region is allowed. In the following, we take $M_R=4.0\times10^{13}$ GeV for the degenerate case, and $M_R=4.0\times10^{14}$ GeV for the nondegenerate case.

3. Parameters in the U(2) model

In the $U(2)$ model, the symmetry breaking parameters ϵ and ϵ' are taken to be $\epsilon=0.04$ and $\epsilon'=0.008$, and the other parameters in the quark Yukawa coupling matrices are determined so that the CKM matrix and the quark masses given in Sec. IV A 1 are reproduced. The detailed discussion to determine the quark Yukawa coupling matrices is given in Ref. [4].

There are many free parameters in the SUSY breaking sector as shown in Eq. (8). In order to reduce the number of free parameters in numerical calculations, we assume that

$$m_0^{Q2}=m_0^{U2}=m_0^{D2}\equiv m_0^2, \tag{24}$$

$$r_{ij}^Q=r_{ij}^U=r_{ij}^D\equiv r_{ij},$$

$$(ij)=(22),(23),(33). \tag{25}$$

We scan the ranges for these parameters as $0<m_0<3\,\mathrm{TeV}$, $-1<r_{22}<+1$, $0<r_{33}<4$, $|r_{23}|<4$, and $-180°<\arg r_{23}<180°$. We assume that the boundary conditions for the A parameters are the same as the mSUGRA case for simplicity.

B. Experimental constraints

In order to obtain allowed regions of the parameter space, we consider the following experimental results:

TABLE III. The relation between the Wilson coefficients and the observables. √ means that the coefficient gives a main contribution to the observables.

	$A_{CP}^{\rm dir}(B\to X_s\gamma)$	$A_{CP}^{\rm mix}(B_d\to M_s\gamma)$	$A_{CP}^{\rm mix}(B_d\to\phi K_S)$
C_{7L}	√	√	-
C_{7R}	-	√	-
C_{8L}	√	-	√
C_{8R}	-	-	√

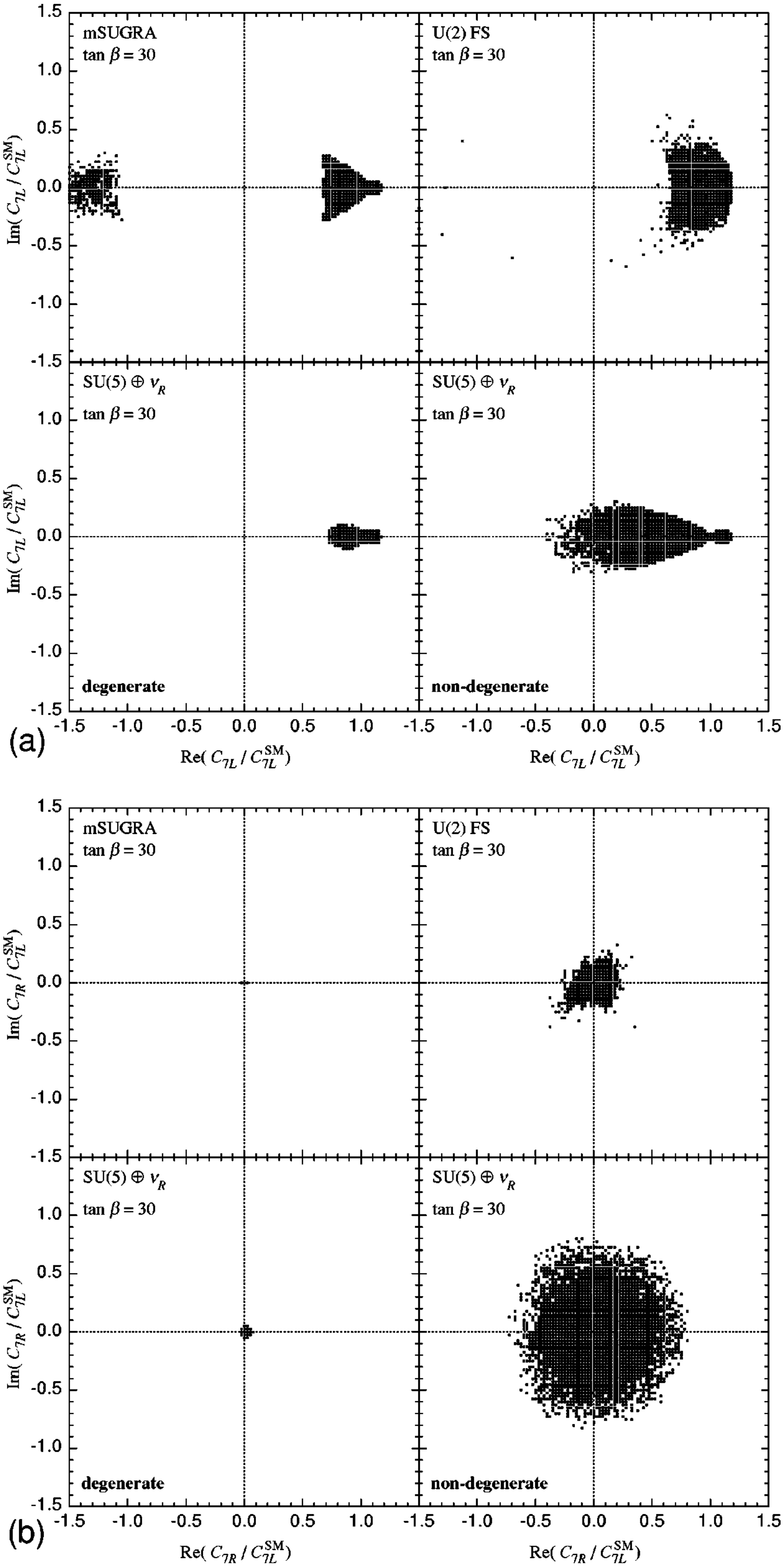

FIG. 4. Wilson coefficients (a) C_{7L} and (b) C_{7R} normalized by the SM value of C_{7L}.

(i) Lower limits on the masses of SUSY particles and the Higgs bosons given by direct searches in collider experiments [46].

(ii) Branching ratio of the $b \to s\gamma$ decay: $2\times10^{-4} < \mathrm{B}(b \to s\gamma) < 4.5\times10^{-4}$ [47].

(iii) Upper bound of the branching ratio of the $\mu\to e\gamma$ decay for the SUSY GUT cases: $\mathrm{B}(\mu\to e\gamma) < 1.2\times10^{-11}$ [48].

(iv) Upper bounds of EDMs of the neutron and the electron: $|d_n| < 6.3\times10^{-26} e\cdot\mathrm{cm}$ [28] and $|d_e| < 4.0\times10^{-27}$

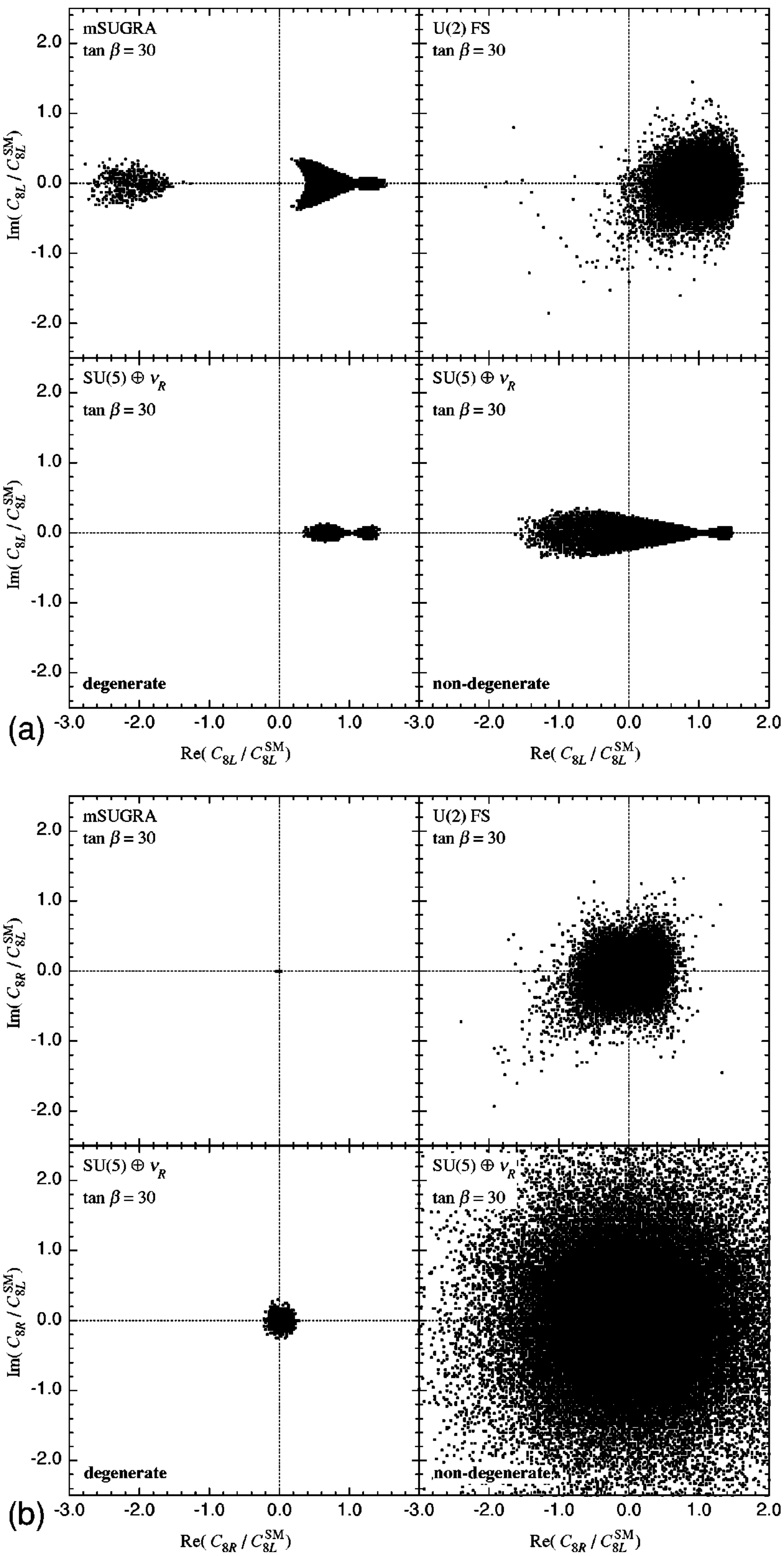

FIG. 5. Wilson coefficients (a) C_{8L} and (b) C_{8R} normalized by the SM value of C_{8L}.

TABLE IV. Possible SUSY contributions to Wilson coefficients C_7's and C_8's and $M_{12}(B_s)$ in each model. √ means non-negligible deviation from the SM, and √√ denotes large SUSY contributions.

	mSUGRA	$SU(5)$ SUSY GUT degenerate	$SU(5)$ SUSY GUT non-degenerate	$U(2)$
$\|C_{7,8L}\|$	-	-	√√	√√
$\|C_{7,8R}\|$	-	√	√√	√√
$\arg C_{7,8L}$	√	-	√	√√
$\arg C_{7,8R}$	-	√	√√	√√
$M_{12}(B_s)$	-	-	√√	√√

$\times e\cdot$cm [29].

(v) The CP violation parameter ε_K in the K^0–$\overline{K}^0$ mixing and the B_d–$\overline{B}_d$ mixing parameter Δm_{B_d} [49]. As for the B_s–$\overline{B}_s$ mixing parameter Δm_{B_s}, we take $\Delta m_{B_s} > 13.1$ ps^{-1} [50].

(vi) CP asymmetry in the $B \to J/\psi K_S$ decay and related modes observed at the B factory experiments [1].

C. Numerical results

1. Unitarity triangle analysis

As in our previous work [4], we search possible values of $A_{CP}^{\rm mix}(B_d \to J/\psi K_S)$, Δm_{B_s}, Δm_{B_d}, and ϕ_3 under the constraints stated above. The results for the mSUGRA and the $U(2)$ model are not shown here, since they are similar as Fig. 5 in Ref. [4] apart from slight changes in some input parameters.

In Fig. 2, we show the above quantities in the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos for $\tan\beta = 30$ as well as the degenerate case. In the degenerate case, as we found in our previous paper [4], the SUSY contribution to the K^0–$\overline{K}^0$ mixing is large and ε_K is significantly affected. This is because of the large 1–2 mixing in the squark sector. However, the SUSY contributions to the B_d–$\overline{B}_d$ mixing and the B_s–$\overline{B}_s$ mixing are not important. Thus the correlation among $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\rm mix}(B_d \to J/\psi K_S)$, and ϕ_3 is very similar as the SM. On the other hand, in the nondegenerate case, the 2–3 mixing in the squark sector is enhanced, and the 1–2 mixing and the 1–3 mixing are suppressed. This means that the correlation among $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\rm mix}(B_d \to J/\psi K_S)$, and ϕ_3 may differ from the SM, because of non-negligible SUSY contributions to the B_s–$\overline{B}_s$ mixing.

From this figure, we see that the allowed range of ϕ_3 depends on the value of $\Delta m_{B_s}/\Delta m_{B_d}$ in each case. For example, if $\Delta m_{B_s}/\Delta m_{B_d}$ is consistent with the SM (~ 35), we observe $\phi_3 \sim 60°$ in the degenerate case, and $45° \lesssim \phi_3 \lesssim 75°$ in the nondegenerate case. In the case that $\Delta m_{B_s}/\Delta m_{B_d}$ is larger than the SM, e.g., $\Delta m_{B_s}/\Delta m_{B_d} \sim 55$, ϕ_3 is $\sim 40°$ in the degenerate case, while the allowed range is expected as $45° \lesssim \phi_3 \lesssim 60°$ in the nondegenerate case. This indicates that a ϕ_3 measurement is important to distinguish the two cases. In Table II, we summarize possible deviations of ϕ_3 and Δm_{B_s} from the SM in each model.

In the above and the following numerical calculations, as mentioned in the introduction, we do not take the $\tan\beta$-enhanced radiative corrections in the neutral Higgs couplings into account. These corrections could be significant for the $B-\overline{B}$ mixing amplitudes in the parameter regions of large values of $\tan\beta$ and small masses of the heavy Higgs bosons because they scale as $(\tan\beta)^4/(m_{H^\pm})^2$ [23]. Accordingly, it is unlikely that this effect changes our numerical results momentously in the region $\tan\beta \lesssim 30$. As for $B_d \to \phi K_S$, it is shown by Kane *et al.* [11] that the contribution from the neutral Higgs exchange diagrams is small.

In Fig. 3, we show allowed regions in the $\mathrm{Re}\, M_{12}(B_s)$ and $\mathrm{Im}\, M_{12}(B_s)$ plane for the three models in the case of $\tan\beta = 30$. In the mSUGRA, the deviation from the SM is less than 5%, and the SUSY contributions to the complex phase of $M_{12}(B_s)$ are negligible. In the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos, the SUSY contribution is large in both the real and the imaginary parts of $M_{12}(B_s)$. They can be as large as 30% of the SM contribution to $|M_{12}(B_s)|$. This is in contrast with the degenerate case. As seen in Fig. 3, the SUSY contribution to $M_{12}(B_s)$ in the degenerate case is tiny, since the constraint to the parameter space imposed by the $\mu \to e\gamma$ branching ratio is very strict. In the $U(2)$ model, there are SUSY corrections of the order of 20% or larger to $M_{12}(B_s)$. We have studied the case of $\tan\beta = 5$ as well. We have found that the allowed regions of $M_{12}(B_s)$ are similar to those for $\tan\beta = 30$. From the experimental point of view, $\Delta m_{B_s} = 2|M_{12}(B_s)|$ will be measured by using B_s decays such as $B_s \to D_s\pi$ in hadron B experiments [2]. The phase of $M_{12}(B_s)$ can be measured by observing CP violation in B_s decays such as $B_s \to J/\psi\phi$.

2. Rare B decays

Here, we discuss rare B decays in the three models. We first present SUSY contributions to the Wilson coefficients of the dipole operators C_{7L}, C_{7R}, C_{8L}, and C_{8R}. In Table III, we show the relation between these Wilson coefficients and observables.

The real and imaginary parts of C_{7L} and C_{7R} at the bottom mass scale divided by the SM value of C_{7L} are plotted in Fig. 4 for $\tan\beta = 30$. For $\tan\beta = 5$, SUSY contributions are less significant, and we mainly consider the $\tan\beta = 30$ case in the following.

In the leading order approximation, the branching ratio of $b \to s\gamma$ is proportional to $|C_{7L}|^2 + |C_{7R}|^2$. In the mSUGRA, however, the SUSY contributions to C_{7R} is very small,because of no new flavor violation in the right-handed squark sector. Thus, the $b \to s\gamma$ branching ratio constrains $|C_{7L}|$. In addition, the SUSY contributions to the phase of C_{7L}, which is dominated by the phase ϕ_A, is small due to the constraint from the neutron EDM experiment.

In the $SU(5)$ SUSY GUT with right-handed neutrinos, the new flavor mixing in the right-handed squark sector is induced by the MNS matrix and GUT interactions. SUSY contributions to C_{7L} and C_{7R} can be as large as $C_{7L}^{\rm SM}$. The EDM constraints are also strong, and the SUSY contribution

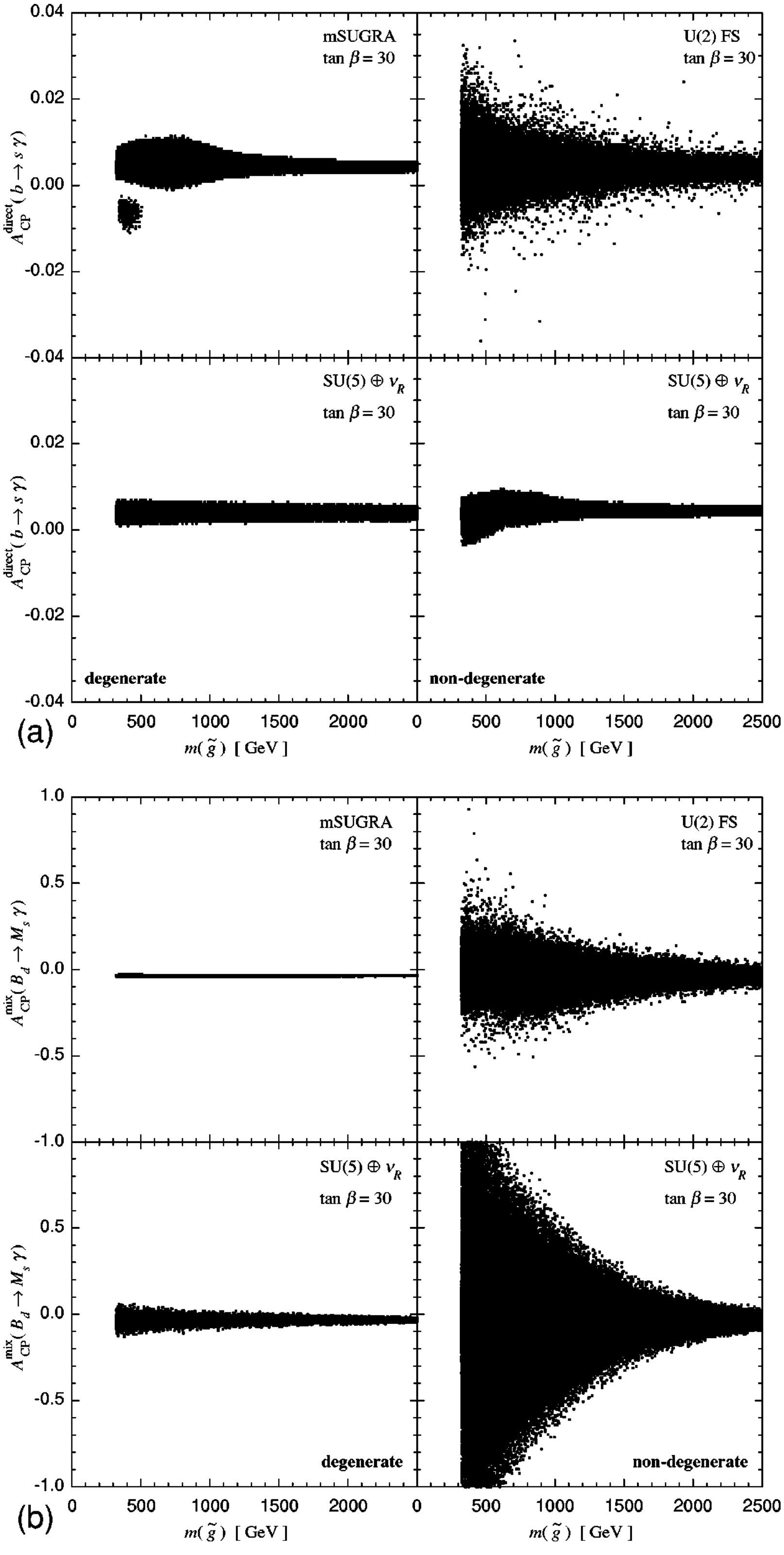

FIG. 6. (a) The direct CP asymmetry in $b \to s\gamma$, and (b) the mixing-induced CP asymmetry in $B_d \to M_s\gamma$ as functions of the gluino mass.

to the phase of C_{7L} cannot become large as in the mSUGRA. Since we have introduced no CP phase of the neutrino sector in this analysis, the SUSY contribution to the phase of C_{7R} mainly comes from the GUT phases ϕ_i^L. Note that ϕ_i^L's contribute only to off-diagonal elements of the right-handed down squark mass matrix, and thus, they do not affect the neutron EDM. The $\mu \to e\gamma$ constraint in the degenerate case is much stronger than that in the nondegenerate case as seen in Fig. 1. Therefore, the allowed regions become much larger in the nondegenerate case.

In the $U(2)$ model, SUSY contributions to C_{7L} and C_{7R} can be large because of the existence of new flavor mixings

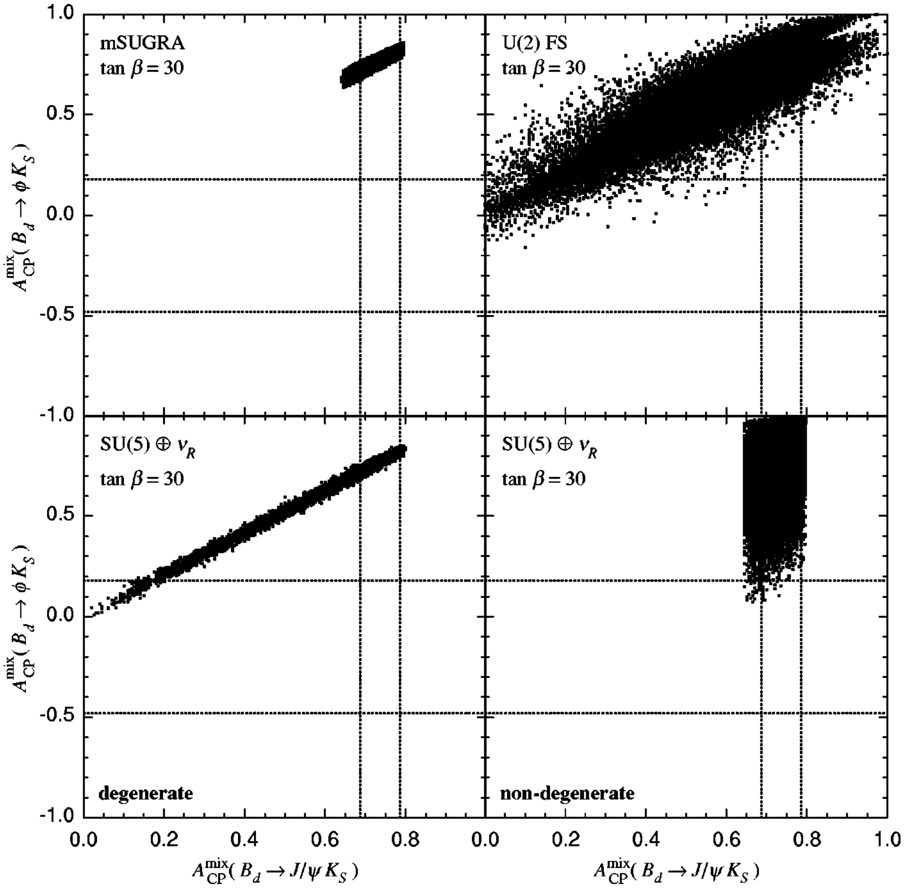

FIG. 7. The correlation between the mixing-induced CP asymmetries in $B_d\to\phi K_S$ and $B_d\to J/\psi K_S$. The vertical and horizontal dotted lines show the 1σ ranges of experimental values. In this plot, the experimental constraint of $A^{\rm mix}_{CP}(B_d\to J/\psi K_S)$ is not imposed.

in the squark sector. Though the new contribution to the phase of C_{7L} is restricted by the neutron EDM constraint in this model, the restriction is weaker than that in the above two models because the phase of $(m^2_Q)_{23}$ is independent of the phase that contributes to the neutron EDM. Compared with the nondegenerate case of $SU(5)$ SUSY GUT with right-handed neutrinos, $|(m^2_D)_{23}|$ is suppressed in the $U(2)$ model, and the SUSY contribution to $|C_{7R}|$ is smaller.

The SUSY contributions to C_{8L} and C_{8R} are similar to those to C_{7L} and C_{7R} in each model as seen in Fig. 5, because the flavor mixings and CP phases that determine the SUSY contributions to C_{7L} and C_{7R} are the same as those contribute to C_{8L} and C_{8R}. This means that the constraints on C_{7L} and C_{7R} from $b\to s\gamma$ branching ratio also restrict predicted values of C_{8L} and C_{8R}. In Table IV, we summarize possible SUSY contributions to Wilson coefficients C_7's and C_8's and $M_{12}(B_s)$ in each models.

In Fig. 6, we plot $A^{\rm dir}_{CP}(B\to X_s\gamma)$ and $A^{\rm mix}_{CP}(B\to M_s\gamma)$ versus the gluino mass for $\tan\beta=30$. $A^{\rm dir}_{CP}(B\to X_s\gamma)$ essentially comes from the imaginary part of the interference terms between C_{7L} and C_{2L}, and C_{8L} and C_{2L}, because C_{2R} is negligible. Therefore, SUSY contributions to $A^{\rm dir}_{CP}(B\to X_s\gamma)$ is constrained by the neutron EDM, and $|A^{\rm dir}_{CP}(B\to X_s\gamma)|$ is at most $\sim 1\,\%$ in the mSUGRA and the $SU(5)$ SUSY GUT with right-handed neutrinos. $|A^{\rm dir}_{CP}(B\to X_s\gamma)|$ can be as large as $3\,\%$ in the $U(2)$ model. The SM prediction is about $0.5\,\%$ [15]. On the other hand, the mixing-induced CP asymmetry in $B_d\to M_s\gamma$ depends on C_{7L} and C_{7R}. Although the SUSY contribution to C_{7L} cannot be negligible in the models that we are studying, the deviation from the SM essentially comes from C_{7R}. Therefore, the SUSY effect can become larger in the $SU(5)$ SUSY GUT with right-handed neutrinos and in the $U(2)$ model compared with the mSUGRA model. In the mSUGRA model, $|A^{\rm mix}_{CP}(B\to M_s\gamma)|$ is at a level of $1\,\%$, which is similar to the value of the SM [16]. In the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos, $|A^{\rm mix}_{CP}(B_d\to M_s\gamma)|$ can be maximal, while in the degenerate case, $|A^{\rm mix}_{CP}(B_d\to M_s\gamma)|$ can be as large as 0.1. In the $U(2)$ model, we find that $|A^{\rm mix}_{CP}(B\to M_s\gamma)|$ could be as large as 0.5.

In Fig. 7, we show the correlation between $A^{\rm mix}_{CP}(B_d\to\phi K_S)$ and $A^{\rm mix}_{CP}(B_d\to J/\psi K_S)$ for $\tan\beta=30$. In the SM, $A^{\rm mix}_{CP}(B_d\to\phi K_S)=A^{\rm mix}_{CP}(B_d\to J/\psi K_S)$ is satisfied. As mentioned in Sec. III, the SM contribution is dominant in C_{LL}, $C^{(1)}_{LR}$, and $C^{(2)}_{LR}$ due to the QCD correction between the electroweak scale and the bottom mass scale. Thus, SUSY contributes to $A^{\rm mix}_{CP}(B_d\to\phi K_S)$ mainly through C_8's.

In the mSUGRA, we see that the SM relation $A^{\rm mix}_{CP}(B_d\to\phi K_S)=A^{\rm mix}_{CP}(B_d\to J/\psi K_S)$ approximately holds, and the deviation from the SM in $A^{\rm mix}_{CP}(B\to J/\psi K_S)$ is less than $10\,\%$ as seen in Ref. [4]. Therefore, $A^{\rm mix}_{CP}(B\to\phi K_S)$ is almost the same as that in the SM.

In the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos, $A^{\rm mix}_{CP}(B_d\to\phi K_S)$ can substantially differ from the value in the SM and may be smaller than 0.1

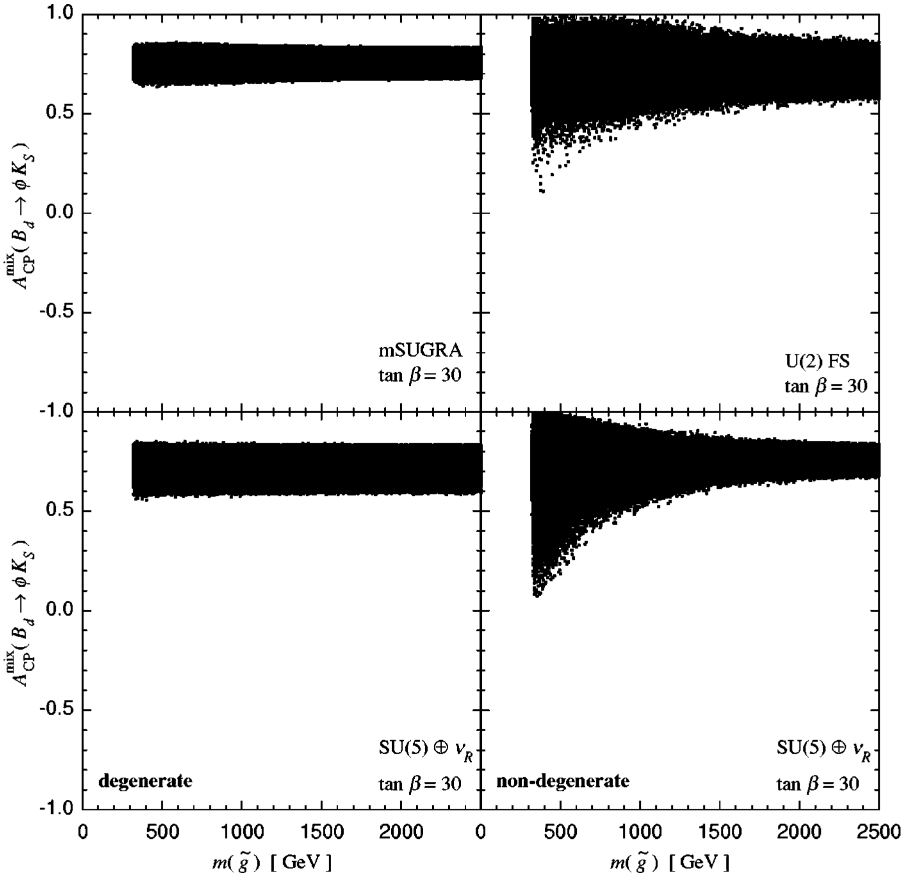

FIG. 8. The mixing-induced CP asymmetry in $B_d \to \phi K_S$ as a function of the gluino mass.

because of the large SUSY contributions to C_{8R}. On the other hand, in the degenerate case, the SM relation $A^{\rm mix}_{CP}(B_d \to \phi K_S) = A^{\rm mix}_{CP}(B_d \to J/\psi K_S)$ is satisfied. Accordingly, the value of $A^{\rm mix}_{CP}(B_d \to \phi K_S)$ is restricted by the experimental result on $A^{\rm mix}_{CP}(B_d \to J/\psi K_S)$.

In the $U(2)$ model, $A^{\rm mix}_{CP}(B \to \phi K_S)$ can deviate from the SM prediction because of SUSY contributions to C_{8L} and C_{8R}. The experimental result of $A^{\rm mix}_{CP}(B_d \to J/\psi K_S)$ implies that $A^{\rm mix}_{CP}(B_d \to \phi K_S)$ lies between 0.3 and 1.0.

In Fig. 8, we show $A^{\rm mix}_{CP}(B_d \to \phi K_S)$ as a function of the gluino mass. In the mSUGRA and the degenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos, the SUSY effect is almost negligible and we see virtually no dependence on the gluino mass. On the other hand, in the degenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos and the $U(2)$ model, the SUSY contribution is significant, in particular, for the smaller mass of the gluino.

Recently, it has been pointed out that the contribution of the chromo-EDM of the strange quark to the EDM of ^{199}Hg is devastating in SUSY models with a large 2–3 mixing in the right-handed squark sector, and that a large deviation of $A^{\rm mix}_{CP}(B_d \to \phi K_S)$ from the SM prediction is unlikely provided that the experimental upper bound [51] on the EDM of ^{199}Hg is imposed [52]. Although the theoretical estimate [53] of the ^{199}Hg EDM due to the chromo-EDM of the light quarks

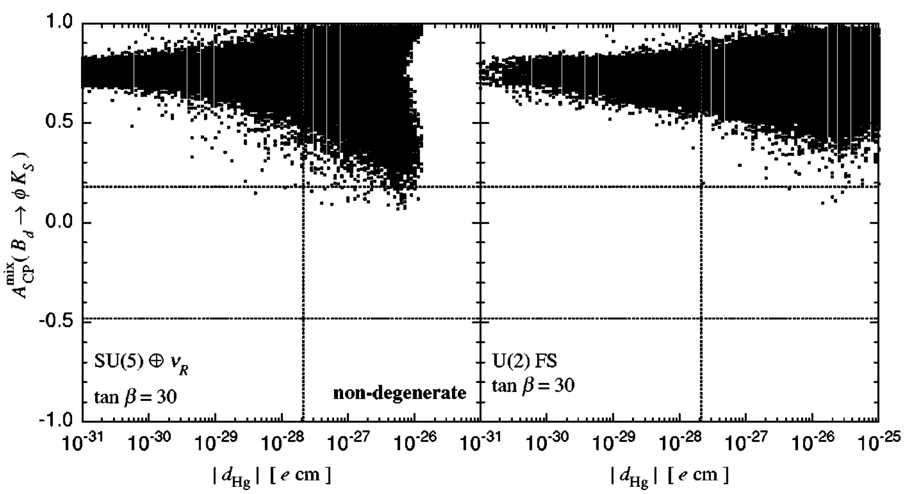

FIG. 9. The correlation between the mixing-induced CP asymmetry in $B_d \to \phi K_S$ and the ^{199}Hg EDM in the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos and the $U(2)$ model.

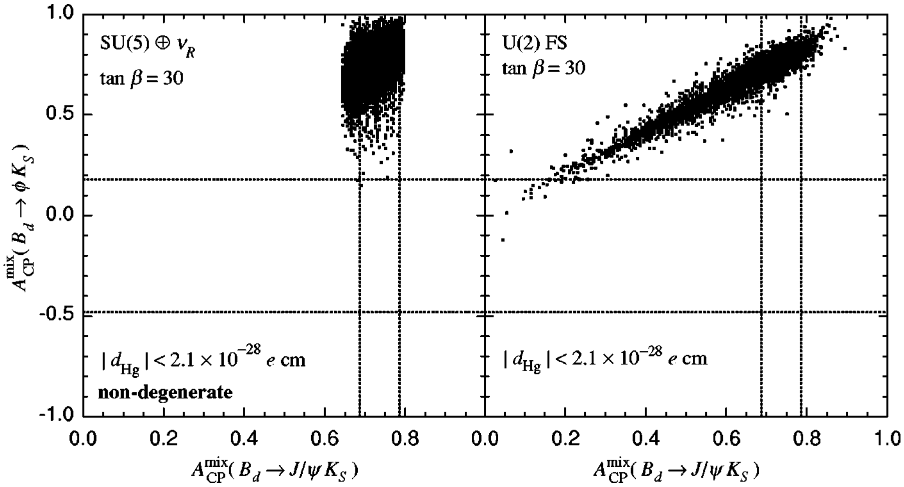

FIG. 10. The correlation between the mixing-induced CP asymmetries in $B_d \to \phi K_S$ and $B_d \to J/\psi K_S$ under the constraint of the ^{199}Hg EDM in the nondegenerate case of the $SU(5)$ SUGY GUT with right-handed neutrinos and the $U(2)$ model.

suffers from relatively large uncertainties, it is probable that the ^{199}Hg EDM constraint severely restricts flavor mixings and CP violation in some SUSY models, and thus constricts their flavor and CP signals, such as $A^{mix}_{CP}(B_d \to \phi K_S)$ in general.

Among the models considered in the present work, effects of the ^{199}Hg EDM constraint are non-negligible in the nondegenerate case of the $SU(5)$ SUSY GUT with right-handed neutrinos and the $U(2)$ model. We show the correlation between the ^{199}Hg EDM and $A^{mix}_{CP}(B_d \to \phi K_S)$ in these models in Fig. 9. In our numerical calculation of the ^{199}Hg EDM, contributions of all three light flavors are included. Figure 9 illustrates how a flavor signal is tightened if the ^{199}Hg EDM constraint is applied. In Fig. 10, the correlation between $A^{mix}_{CP}(B_d \to J/\psi K_S)$ and $A^{mix}_{CP}(B_d \to \phi K_S)$ under the constraint of the ^{199}Hg EDM is shown. Comparing this figure with Fig. 7, we see that the ^{199}Hg EDM constraint certainly restricts the possible deviation from the SM prediction. At the same time, however, our detailed calculation shows that there still remains some parameter region in which $A^{mix}_{CP}(B_d \to \phi K_S)$ is significantly different from $A^{mix}_{CP}(B_d \to J/\psi K_S)$ in these models. A similar argument is applied to both $A^{dir}_{CP}(B \to X_s \gamma)$ and $A^{mix}_{CP}(B \to M_s \gamma)$.

In Table V, we summarize the significance of SUSY contributions on the CP asymmetries that we have considered. In this table, we see the possibility to distinguish the three models in B experiments.

As we stressed in the introduction, the purpose of this work is to demonstrate that identifying patterns of deviations from the SM predictions is useful to distinguish different origins of the SUSY breaking sector. From this point of view, combined with the analysis of the unitarity triangle [4], we can make the following observations:

(i) Deviations from the SM predictions in the unitarity triangle and rare decays are small in the mSUGRA model, except for some sizable contributions in the direct CP violation in the $b \to s \gamma$ process. Note that this conclusion may not hold in a particularly large value of $\tan\beta \sim 60$ due to the Higgs exchange effects [23].

(ii) The pattern of the deviations from the SM depends on the right-handed neutrino mass matrix in the $SU(5)$ SUSY GUT with right-handed neutrinos. In the degenerate case, flavor-mixing signals between the 1–2 generations become large. This appears as inconsistency between the measured value of ϵ_K and the B meson unitarity triangle, although the unitarity triangle is closed among B meson observables. The rare decay processes induced by the $b-s$ transition do not show large deviations, but the branching ratio of $\mu \to e \gamma$ process can be just below the present experimental bound. This is expected to be a generic feature of $SU(5)$ SUSY GUT with right-handed neutrinos.

(iii) In a specific parameter choice of the "nondegenerate" case, in which the $\mu \to e \gamma$ constraint is relaxed, the flavor signals between 2–3 generations are expected to be sizable. This includes the mixing-induced CP asymmetry in $B_d \to M_s \gamma$ and $B_d \to \phi K_S$. The direct CP asymmetry in the $b \to s \gamma$ process, on the other hand, does not show a large deviation.

(iv) Various new physics signals in the consistency test of the unitarity triangle and rare decay process are expected in the MSSM with $U(2)$ flavor symmetry.

In this way, we can expect different sizes and patterns of new physics signals in the above models. These are crucial in pointing toward a specific model from flavor physics.

TABLE V. Significance of SUSY contributions to the CP asymmetries in each model. √ means non-negligible deviation from the SM, and √√ means large SUSY contributions.

		$SU(5)$ SUSY GUT		
	mSUGRA	degenerate	non-degenerate	$U(2)$
$A^{dir}_{CP}(B \to X_s \gamma)$	√	-	√	√√
$A^{mix}_{CP}(B \to M_s \gamma)$	-	√	√√	√√
$A^{mix}_{CP}(B \to \phi K_S)$	-	-	√√	√√

V. CONCLUSIONS

In order to seek the possibility to distinguish different SUSY models with B physics experiments, we have studied rare B decays related to the $b \to s$ transition combining with the unitarity triangle analysis in three SUSY models. These models, namely, the mSUGRA, the $SU(5)$ SUSY GUT with right-handed neutrinos, and the $U(2)$ flavor symmetry model, are different in character with respect to flavor structures of their SUSY breaking sectors. We have considered two different cases in regard to the mass spectrum of the right-handed neutrinos in the $SU(5)$ SUSY GUT with right-handed neutrinos.

In the unitarity triangle analysis, we have studied consequences of SUSY to $A_{CP}^{\mathrm{mix}}(B_d \to J/\psi K_S)$, $\Delta m_{B_s}/\Delta m_{B_d}$, and ϕ_3. Our results are summarized in Table II and Fig. 2. It could be possible to distinguish the three models by precisely measuring Δm_{B_s} and ϕ_3 in future B experiments.

As for rare B decays, we have explored SUSY effects to the direct CP asymmetry in $b \to s\gamma$, the mixing induced CP asymmetry in $B_d \to M_s\gamma$, and the CP asymmetry in $B_d \to \phi K_S$ in the three models. The results are summarized in Tables IV and V. Table IV shows the relative importance of SUSY contributions to the theoretically interesting Wilson coefficients related to the $b \to s$ transitions and the B_s–$\overline{B}_s$ mixing amplitude. The significance of SUSY effects to the CP asymmetries is indicated in Table V.

The new flavor signals in the mSUGRA and the degenerate case of the $SU(5)$ SUSY GUT are relatively limited in the $b \to s$ rare decays considered in the present work. To detect these signals, typically a few percent, we may need an ultimate B experiment.

On the other hand, the nondegenerate case of the $SU(5)$ SUSY GUT exhibits quite attractive flavor signals in $B_d \to M_s\gamma$ and $B_d \to \phi K_S$ as seen in Table V. We have also observed that the $U(2)$ model predicts significant deviations from the SM in the $b \to s$ rare decays as well as the unitarity triangle analysis. So far, both Belle and BaBar experiments have collected copious B decays, and they are expected to go well continuously. Thus, more $B_d \to \phi K_S$ and related events will be obtained in near future. Moreover, both KEK and SLAC plan to upgrade their B factories. Therefore, the above flavor signals may well be in the reach of the present and foreseeable future B experiments.

Combining the above observation with the results in our previous work, we conclude that the study of the unitarity triangle and rare B decays could discriminate several SUSY models that have different flavor structures in their SUSY breaking sectors. Such a study will play important roles, even if SUSY particles are found at future experiments at the energy frontier, such as LHC. Although the spectrum of SUSY particles will be determined at LHC and a future e^+e^- linear collider, most of information concerning the flavor mixing of the squark sector is expected to come from the super B factory and hadron B experiments. Since the flavor structure of the SUSY breaking provides us with an important clue to the origin of the SUSY breaking mechanism and interactions at very high energy scales, B physics will be essential for clarifying a whole picture of the SUSY model.

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