CP violating *B* decays with *R*-parity violation

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(Received 25 August 1998; published 21 July 1999)

We study CP violating B decays in the minimal supersymmetric standard model with R-parity violation. We estimate how much R-parity violation modifies the SM predictions for CP asymmetries in B decays within the present bounds. The effects of R-parity- and lepton-number-violating couplings on the ratio of the decay amplitude due to R-parity violation to that of the SM can differ by one or two orders of magnitudes depending on the models of the left-handed quark mixing. It is possible to disentangle the R-parity-violating effects from those of the SM and R-parity-conserving supersymmetric models within the present bounds comparing different CP violating decay amplitudes. We also study the effects of R-parity- and baryon-number-violating couplings and find that the effects could be large. [S0556-2821(99)00215-5]

PACS number(s): 13.25.Hw, 11.30.Er, 11.30.Fs

I. INTRODUCTION

In the upcoming experiments at B factories, large data samples will be acquired [1]. One of the most important objectives of these experiments is a search for CP violation in B decays. The large data on B meson will enable us to probe physics beyond the standard model (SM) via CP violating B decays. In a supersymmetric extension of the SM, there are many potential sources for CP violation in addition to the SM Cabibbo-Kobayashi-Maskawa (CKM) phase. So the SM predictions on CP asymmetries in B decays can be modified. The nondiagonality of the sfermion mass matrices in a basis where all the couplings of neutral gauginos to fermions and sfermions are flavor diagonal can change the SM predictions on CP violation [2]. The SM predictions can also be modified by the so-called R-parity-violating terms.

In supersymmetric models, there are gauge-invariant interactions which violate baryon number B and lepton number L generically. To prevent the presence of these B- and L-violating interactions in supersymmetric models, an additional global symmetry is required. This requirement leads to the consideration of the so-called R parity. R parity is given by the relation $R_p=(-1)^{(3B+L+2S)}$ where S is the intrinsic spin of a field. Even though the requirement of R_p conservation gives a theory consistent with present experimental searches, there is no good theoretical justification for this requirement. Therefore models with explicit R_p violation ($\not{R}_p$) have been considered by many authors [3].

In this paper, we wish to study CP violating B decays in the minimal supersymmetric standard model (MSSM) with $\not{R}_p$. We investigate how much $\not{R}_p$ modifies the SM predictions for CP asymmetries in B decays within the present bounds. We emphasize that the effects of R_p and L violation on the ratio of the decay amplitude due to $\not{R}_p$ to that of the SM can differ by one or two orders of magnitudes depending on the models of the left-handed quark mixing. We also study the effects of R_p and B violation.

In the MSSM the most general R_p violating superpotential is given by

$$W_{\not{R}_p}=\lambda_{ijk}L_iL_jE_k^c+\lambda'_{ijk}L_iQ_jD_k^c+\lambda''_{ijk}U_i^cD_j^cD_k^c. \quad (1)$$

Here i,j,k are generation indices and we assume that possible bilinear terms $\mu_iL_iH_2$ can be rotated away. L_i and Q_i are the SU(2)-doublet lepton and the quark superfields and E_i^c,U_i^c,D_i^c are the singlet superfields, respectively. λ_{ijk} and λ''_{ijk} are antisymmetric under the interchange of the first two and the last two generation indices, respectively; $\lambda_{ijk}=-\lambda_{jik}$ and $\lambda''_{ijk}=-\lambda''_{ikj}$. So the number of couplings is 45 (9 of the λ type, 27 of the λ' type, and 9 of the λ'' type). Among these 45 couplings, 36 couplings are related with the lepton flavor violation.

There are upper bounds on a *single* L- and R_p-violating couplings from several different sources [4–7,9]. Among these, upper bounds from atomic parity violation and eD asymmetry [4], ν_μ deep-inelastic scattering [4], neutrinoless double-beta decay [5], ν mass [6], K^+,t-quark decays [7,8], and Z decay width [9] are strong. Neutrinoless double-beta decay gives $\lambda'_{111}<3.5\times10^{-4}$. The bounds from ν mass are $\lambda_{133}<3\times10^{-3}$ and $\lambda'_{133}<7\times10^{-4}$.

There are strong bounds on $\lambda'_{ijk}<0.012$ for $j=1$ and 2 from K^+-meson decays. But these single bounds depend on the models of the left-handed quark mixing. The CKM matrix consists of the product of the mixing matrices of the left-handed up- and down-type quarks and we do not know the mixings of the up- and down-type quarks separately. Therefore, in this case, we need some assumptions about the mixings of the left-handed quarks to derive a single bound on λ' coupling from the physical process. The bounds of $\lambda'_{i(1,2)k}<0.012$ are valid only when the mixing of the down-type quarks dominates the CKM matrix. On the contrary, if the mixing of the up-type quarks dominates the CKM matrix, the bounds on $\lambda'_{i(1,2)k}$ are totally invalid. In the general case where the CKM matrix has contributions from the up-quark sector as well as down-quark sector, the bounds from K^+-meson decays become invalid and the typical bounds on λ'_{ijk} with $j=2,3$ and $\lambda'_{123,132}$ are $\mathcal{O}(0.1)$. We consider the general case as well as the case in which the single bounds

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from K^+-meson decays are valid. We find that the effects of R_p violation can differ by one or two orders of magnitudes depending on the models of the left-handed quark mixing.

The upper bounds on B- and R_p-violating couplings are $\mathcal{O}(1)$ except $\lambda''_{112}<10^{-6}$ and $\lambda''_{113}<10^{-4}$ from the double-nucleon decay and n-$\overline{n}$ oscillation, respectively.

In this paper we assume that all masses of scalar partners which mediate the processes are 100 GeV. Extensive reviews of the limits on a single R_p-violating coupling can be found in [10].[1]

There are more stringent bounds on some products of the R_p-violating couplings from the mixings of the neutral K and B mesons and the rare leptonic decays of the K_L meson, the muon, and the tau [8], $b\overline{b}$ productions at the CERN e^+e^- collider LEP [11], the rare leptonic and semileptonic B^0 decays [12–14], muon(ium) conversion, and τ and π^0 decays [15].

The CP violating decays of B mesons can be induced by the baryon-number-violating couplings as well as by the lepton-number-violating ones. But the baryon-number and the lepton-number-violating couplings cannot coexist in order to avoid too fast proton decays. So we will consider the baryon-number-violating case and the lepton-number-violating one separately.

About the baryon-number-violating coupling, there is a very strong upper bound on $\lambda''_{112}<10^{-15}$ from the proton decay in gauge-mediated supersymmetry-breaking models independently of the lepton-number-violating couplings [16]. Recently, a study of the one-loop structure of the proton decay into a very light gravitino or axino shows that all baryon-number-violating couplings are constrained as $\lambda''_{\rm any}<10^{-6}$ even though these bounds depend on the precise value of the gravitino mass or the scale of spontaneous $\mathrm{U}(1)_{PQ}$ breaking [17].

This paper is organized as follows. In Sec. II, we introduce the general formalism for the CP asymmetry in the case where the decay amplitude contains contributions from two terms. In Sec. III, we consider the effects of R_p- and lepton-number-violating couplings on the CP asymmetries of neutral B mesons. And the effects of R_p- and baryon-number-violating couplings on the CP asymmetries are considered in Sec. IV. We conclude in Sec. V.

II. GENERAL FORMALISM

The time-dependent CP asymmetry is defined as

$$a_{f_{CP}}(t)\equiv\frac{\Gamma[B^0(t)\to f_{CP}]-\Gamma[\overline{B}^0(t)\to f_{CP}]}{\Gamma[B^0(t)\to f_{CP}]+\Gamma[\overline{B}^0(t)\to f_{CP}]},\tag{2}$$

where f_{CP} denotes the CP eigenstates into which the neutral B mesons decay, and $B^0(t)$ and $\overline{B}^0(t)$ are the states that were tagged as pure B_d and $\overline{B}_d$ at the production. This CP asymmetry can be rewritten by

$$a_{f_{CP}}(t)=a^{\cos}_{f_{CP}}\cos(\Delta Mt)+a^{\sin}_{f_{CP}}\sin(\Delta Mt),\tag{3}$$

where ΔM is the mass difference between the two physical states, and

$$a^{\cos}_{f_{CP}}=\frac{1-|\lambda|^2}{1+|\lambda|^2},\quad a^{\sin}_{f_{CP}}=-\frac{2\,\mathrm{Im}\lambda}{1+|\lambda|^2}.\tag{4}$$

Here λ is given by

$$\begin{aligned}\lambda&=\sqrt{\frac{\langle\overline{B}^0|\mathcal{H}_{\rm eff}|B^0\rangle}{\langle B^0|\mathcal{H}_{\rm eff}|\overline{B}^0\rangle}}\frac{\langle f_{CP}|\mathcal{H}_{\rm eff}|\overline{B}^0\rangle}{\langle f_{CP}|\mathcal{H}_{\rm eff}|B^0\rangle}\\&\equiv e^{-2i\phi_M}\frac{\overline{A}}{A},\end{aligned}$$

$$\langle B^0|\mathcal{H}_{\rm eff}|\overline{B}^0\rangle\equiv M_{12}-\frac{i}{2}\Gamma_{12}=\left|M_{12}-\frac{i}{2}\Gamma_{12}\right|e^{2i\phi_M},\tag{5}$$

using $M_{12}\gg\Gamma_{12}$.

New physics (NP) modifies the SM predictions on both ϕ_M and A. NP affects the B-$\overline{B}$ mixing phase as follows:

$$\phi_M=\phi_M^{\rm SM}+\delta\phi_M,$$

$$\delta\phi_M=\frac{1}{2}\arctan\left(\frac{r_M\sin2(\phi_M^{\rm NP}-\phi_M^{\rm SM})}{1+r_M\cos2(\phi_M^{\rm NP}-\phi_M^{\rm SM})}\right),\tag{6}$$

where $\phi_M^{\rm NP}$ and $\phi_M^{\rm SM}$ are defined by

$$\langle B^0|\mathcal{H}^{\rm full}_{\rm eff}|\overline{B}^0\rangle=|M_{12}^{\rm SM}|e^{2i\phi_M^{\rm SM}}(1+r_Me^{2i(\phi_M^{\rm NP}-\phi_M^{\rm SM})}),\tag{7}$$

where $r_M\equiv|M_{12}^{\rm NP}|/|M_{12}^{\rm SM}|$ and $M_{12}^{\rm NP}\gg\Gamma_{12}^{\rm NP}$ is assumed. For $r_M\ll1, \delta\phi_M\leqslant r_M/2$. However, for $r_M\gg1$, $\delta\phi_M$ can take any value. In the SM, the mixing phase $\phi_M^{\rm SM}$ is β and 0 for B_d-$\overline{B}_d$ and B_s-$\overline{B}_s$, respectively.

If NP contributions to A are dominated by one term and the size of the contribution is larger than that of the subleading SM corrections, A can be written as follows:

$$A=A_{\rm SM}e^{i\phi_1}e^{i\delta_1}+A_{\rm NP}e^{i\phi_2}e^{i\delta_2},$$

$$\overline{A}=A_{\rm SM}e^{-i\phi_1}e^{i\delta_1}+A_{\rm NP}e^{-i\phi_2}e^{i\delta_2},\tag{8}$$

where $A_{\rm SM,NP}$ are real magnitudes, $\phi_{1,2}$ are CP violating phases, and $\delta_{1,2}$ are CP conserving phases. For the sizes of the subleading SM corrections and the contributions of the R_p-conserving supersymmetric model, see Ref. [18].

With $\phi_{12}=\phi_1-\phi_2$, $\delta_{12}=\delta_1-\delta_2$, and $r_D\equiv A_{\rm NP}/A_{\rm SM}$,

$$a^{\cos}_{f_{CP}}=-\frac{2r_D\sin\phi_{12}\sin\delta_{12}}{1+2r_D\sin\phi_{12}\sin\delta_{12}}\approx-2r_D\sin\phi_{12}\sin\delta_{12},$$

[1]The single bounds on λ'_{132}, λ'_{232}, and λ'_{233} should be replaced by 0.16 which are stronger bounds coming from Ref. [13].

$$a_{f_{CP}}^{\sin}=\frac{\sin(2\phi_M+\phi_1)-2r_D\sin\phi_{12}\cos(2\phi_M+2\phi_1+\delta_{12})}{1+2r_D\sin\phi_{12}\sin\delta_{12}}$$
$$\approx\sin 2(\phi_M+\phi_1)-2r_D\sin\phi_{12}\cos 2(\phi_M+\phi_1)\cos\delta_{12}, \tag{9}$$

to the first order in r_D.

For the rest of this paper, we concentrate on $a_{f_{CP}}^{\sin}$. To this end we write

$$a_{f_{CP}}^{\sin}\equiv\sin 2(\phi_M+\phi_1+\delta\phi_D)\equiv\sin 2\phi. \tag{10}$$

For $r_D\ll 1, \delta\phi_D\leqslant r_D$. However, for $r_D\gg 1$, $\delta\phi_D$ can take any value. In the following two sections, we will calculate r_D for several CP violating decay modes.

Note that the NP contribution to the mixing phase ϕ_M is universal for all kinds of decay modes. So one can identify NP contributions to CP violating B decays independently of the NP contribution to the mixing by considering two different decay modes simultaneously.

III. R_p AND L VIOLATION

In this section, we consider the effects of R_p- and lepton-number-violating couplings (λ') assuming that the baryon-number-violating couplings λ'''s vanish.

First, we assume that $V_{\rm CKM}$ is given by only down-type quark sector mixing. In this case, r_M and $r_D(B_d\to\psi K_S,\phi K_S)$ are estimated in Ref. [19] as follows:

$$r_M(B_d)\simeq 10^8|\lambda'_{n13}\lambda'_{n31}|\left(\frac{100\ \text{GeV}}{M_{\tilde\nu}}\right)^2,$$
$$r_D(B_d\to\psi K_S)<0.02,$$
$$r_D(B_d\to\phi K_S)<0.8, \tag{11}$$

and $|\phi(B_d\to\psi K_S)-\phi(B_d\to\phi K_S)|<\mathcal{O}(1)$. $r_M(B_s)$ is given by replacing $|\lambda'_{n13}\lambda'_{n31}|$ with $|\lambda'_{n23}\lambda'_{n32}|$ in $r_M(B_d)$. In this section, we wish to investigate other decay modes and discuss how much the effects of $\not R_p$ differ depending on the models of the left-handed quark mixings.

From Eq. (1), we obtain the following four-fermion effective Lagrangian due to the exchange of the sleptons:

$$\mathcal{L}_{\not R_p}^{\text{eff,2u-2d}}=\frac{4G_F}{\sqrt2}\mathcal{C}_{ijkl}^{\not L}(\overline{d}_iP_Lu_j)(\overline{u}_kP_Rd_l),$$

$$\mathcal{L}_{\not R_p}^{\text{eff,4d}}=\frac{4G_F}{\sqrt2}\mathcal{N}_{ijkl}^{\not L}(\overline{d}_iP_Ld_j)(\overline{d}_kP_Rd_l), \tag{12}$$

where $P_{L,R}=(1\mp\gamma_5)/2$ and the dimensionless couplings $\mathcal{C}_{ijkl}^{\not L}$ and $\mathcal{N}_{ijkl}^{\not L}$ are given by

$$\mathcal{C}_{ijkl}^{\not L}=\frac{\sqrt2}{4G_F}\sum_{n,p,q=1}^{3}\frac{1}{M_{\tilde l_n}^2}V_{kq}V_{jp}^*\lambda'_{npi}\lambda'^*_{nql},$$

$$\mathcal{N}_{ijkl}^{\not L}=\frac{\sqrt2}{4G_F}\sum_{n=1}^{3}\frac{1}{M_{\tilde l_n}^2}\lambda'_{nji}\lambda'^*_{nkl}. \tag{13}$$

From the above effective Lagrangian, we calculate the amplitudes A for the several decay modes under the factorization assumption and the results are shown in the Appendix.

In Table I, we show the R-parity- and lepton-number-violating product combinations which significantly contribute to each process assuming $V_{\rm CKM}$ is given by only down-type quark sector mixing. For the decay mode $B_d\to\psi K_S$, there are four kinds of competitive contributions and the most significant one comes from $\lambda'_{332}\lambda'_{333}$ within present bounds.[2] Typically, the constraints are of the order of 10^{-4} or 10^{-3}. The decay modes with 10^{-3} constraint are $B_d\to\phi K_S$, $B_d\to\pi^0K_S$, $B_s\to\phi K_S$, $B_d\to\phi\pi^0$, and $B_d\to\pi^0\pi^0$. So these five decay modes are important ones in the presence of R_P violation. See Table II for the estimated values of r_D.

The supersymmetric contributions to the decay modes $B_d\to\phi K_S$ and $B_d\to\pi^0K_S$ are not dominated by only $\not R_p$ since there are comparable contributions from nondiagonal sfermion mass matrices to these decay modes; see the second paper of Ref. [18]. And the upcoming B experiments will initially take data at $\Upsilon(4s)$ where only the B_d can be studied and the mode $B_d\to\pi^0\pi^0$ suffers from the large SM uncertainties. For the decay mode $B_d\to\phi\pi^0$, the SM prediction for the branching ratio of this decay mode is quite small: $\mathcal{B}_{\rm SM}(B_d\to\phi\pi^0)=1.9\times10^{-8}$ [20]. Consequently, it would be hard to measure CP violation considering only one decay mode unless $\not R_p$ enhances the branching ratio of this mode significantly. But the R_p- and L-violating effects can be disentangled from those of the SM or R_p-conserving supersymmetric models if we compare two or more decay modes. For example, let us think about the decay modes of $B_d\to\psi K_S$ and $B_d\to\phi K_S$. The difference between CP violating phases of these two decay modes vanishes in the SM or R_p-conserving supersymmetric models. But it does not vanish in the R_p-violating model.

Now, let us think the general case in which the down-type quark mixing does not dominate $V_{\rm CKM}$. In this case, the strong bounds $|\lambda'_{ijk}|<0.012$ with $j=1,2$ from K^+-meson decays becomes invalid. In this case, the typical bounds on λ'_{ijk} with $i=2,3$ are $\mathcal{O}(0.1)$. This means that the constraints given in Table I can become weaker by one or two orders of magnitudes. For example, let us consider the contribution of $\lambda'_{222}\lambda'_{223}$ to the CP asymmetry in the mode $B_d\to\psi K_S$. Neglecting the constraint from K^+ decays, the constraint on this combination is 3.2×10^{-2} from D decay [10]. Using this constraint, one can obtain $r_D(B_d\to\psi K_S)=7.5$. Similarly, we find that the typical size of r_D of *all* decay modes is $\mathcal{O}(1)$ if we neglect the constraint from K^+ decays. It means that it is possible to disentangle the R-parity-violating effects from those of the SM and R-parity-conserving supersymmetric models. In this case, one can also identify the NP effects

[2] In Ref. [19], only the contributions from $\lambda'_{n22}\lambda'_{n23}$ are considered.

TABLE I. R-parity- and lepton-number-violating product combinations which significantly contribute within present bounds [10,13,14] assuming $V_{\rm CKM}$ is given by only down-type quark sector mixing. Constraints on the magnitudes of the product combinations are also shown.

Decay modes	Dominating combination	Constraint
$\overline{B}_d \to \psi K_S$	$\lambda'_{n22}\lambda'_{n23}V_{22}V_{22}$	1.4×10^{-4}
	$\lambda'_{322}\lambda'_{333}V_{23}V_{22}$	2.3×10^{-4}
	$\lambda'_{332}\lambda'_{323}V_{22}V_{23}$	2.3×10^{-4}
	$\lambda'_{332}\lambda'_{333}V_{23}V_{23}$	3.9×10^{-4}
$\overline{B}_d \to \phi K_S$	$\lambda'_{132}\lambda'_{122}$	1.1×10^{-3}
	$\lambda'_{232}\lambda'_{222}$	1.1×10^{-3}
	$\lambda'_{332}\lambda'_{322}$	5.8×10^{-3}
$\overline{B}_d \to \pi^0 K_S$	$\lambda'_{231}\lambda'_{221}$, $\lambda'_{232}\lambda'_{211}$	1.9×10^{-3}
	$\lambda'_{331}\lambda'_{321}$, $\lambda'_{332}\lambda'_{311}$	5.8×10^{-3}
$\overline{B}_d \to D^+ D^-$	$\lambda'_{n21}\lambda'_{n23}V_{22}V_{22}$	1.4×10^{-4}
	$\lambda'_{321}\lambda'_{333}V_{23}V_{22}$	2.3×10^{-4}
	$\lambda'_{331}\lambda'_{323}V_{22}V_{23}$	2.3×10^{-4}
	$\lambda'_{331}\lambda'_{333}V_{23}V_{23}$	3.9×10^{-4}
$\overline{B}_d \to D_{CP}\pi^0(\rho^0)$	$\lambda'_{311}\lambda'_{333}V_{23}V_{11}$	2.3×10^{-4}
	$\lambda'_{311}\lambda'_{323}V_{22}V_{11}$	1.4×10^{-4}
	$\lambda'_{211}\lambda'_{223}V_{22}V_{11}$	1.4×10^{-4}
	$\lambda'_{n21}\lambda'_{n13}V_{11}V_{22}$	1.4×10^{-4}
	$\lambda'_{331}\lambda'_{313}V_{11}V_{23}$	2.3×10^{-4}
$\overline{B}_s \to \phi K_S$	$\lambda'_{132}\lambda'_{121}$, $\lambda'_{132}\lambda'_{112}$, $\lambda'_{232}\lambda'_{221}$, $\lambda'_{232}\lambda'_{212}$, $\lambda'_{231}\lambda'_{222}$	1.9×10^{-3}
	$\lambda'_{332}\lambda'_{321}$, $\lambda'_{331}\lambda'_{322}$, $\lambda'_{332}\lambda'_{312}$	5.8×10^{-3}
$\overline{B}_d \to \phi\pi^0$	$\lambda'_{132}\lambda'_{112}$, $\lambda'_{232}\lambda'_{212}$	1.9×10^{-3}
	$\lambda'_{332}\lambda'_{312}$	5.8×10^{-3}
$\overline{B}_d \to \pi^+\pi^-$	$\lambda'_{211}\lambda'_{213}V_{11}V_{11}$	1.4×10^{-4}
	$\lambda'_{311}\lambda'_{313}V_{11}V_{11}$	1.4×10^{-4}
$\overline{B}_d \to \pi^0\pi^0$	$\lambda'_{231}\lambda'_{211}$	1.9×10^{-3}
	$\lambda'_{331}\lambda'_{311}$	5.8×10^{-3}

independently of the NP contributions to the mixing by taking account of the differences between the angles ϕ's of the first five modes in Table II.

TABLE II. The maximum values of r_D for CP violating B decays with L- and R_p-violating couplings assuming $V_{\rm CKM}$ is given by only down-type quark sector mixing.

Decay mode	Subquark process	$\phi_{\rm SM}$	r_D
$\overline{B}_d \to \psi K_S$	$b\to c\bar{c}s$	β	0.09
$\overline{B}_d \to \phi K_S$	$b\to s\bar{s}s$	β	2.0
$\overline{B}_d \to \pi^0 K_S$	$b\to u\bar{u}s$, $b\to d\bar{d}s$	β	2.8
$\overline{B}_d \to D^+ D^-$	$b\to c\bar{c}d$	β	0.09
$\overline{B}_d \to D_{CP}\pi^0(\rho^0)$	$b\to c\bar{u}d$, $b\to u\bar{c}d$	β	0.06
$\overline{B}_s \to \phi K_S$	$b\to s\bar{s}d$	β	8.0
$\overline{B}_d \to \phi\pi^0$	$b\to s\bar{s}d$	2β	66
$\overline{B}_d \to \pi^+\pi^-$	$b\to u\bar{u}d$	α	0.04
$\overline{B}_d \to \pi^0\pi^0$	$b\to u\bar{u}d$, $b\to d\bar{d}d$	2β	3.0

IV. R_p AND B VIOLATION

In this section, we consider the effects of R_p and the baryon-number-violating couplings (λ'') assuming the lepton number violating couplings λ''s vanish.

From Eq. (1), we obtain the following four-fermion effective Lagrangian due to the exchange of the squarks:

$$
\mathcal{L}^{\rm eff,2u\text{-}2d}_{\not R_p} = \frac{4G_F}{\sqrt{2}}\mathcal{C}^{\not B}_{ijkl}[(\overline{u}_i\gamma^\mu P_R u_j)(\overline{d}_k\gamma_\mu P_R d_l) - (\overline{d}_k\gamma^\mu P_R u_j)(\overline{u}_i\gamma_\mu P_R d_l)],
$$

$$
\mathcal{L}^{\rm eff,4d}_{\not R_p} = \frac{4G_F}{\sqrt{2}}\mathcal{N}^{\not B}_{ijkl}(\overline{d}_i\gamma^\mu P_R d_j)(\overline{d}_k\gamma_\mu P_R d_l), \tag{14}
$$

where $P_{L,R}=(1\mp\gamma_5)/2$ and the dimensionless couplings $\mathcal{C}^{\not B}_{ijkl}$ and $\mathcal{N}^{\not B}_{ijkl}$ are given by

TABLE III. The product combinations which contribute to each decay mode and the maximum values of r_D for CP violating B decays with B- and R_p-violating couplings. Present constraints on the magnitudes of the product combinations are also shown [10,22].

Decay mode	Combination	Constraint	r_D
$\overline{B}_d \to \psi K_S$	$\lambda''_{212}\lambda''_{213}$	6.4×10^{-3}	12
$\overline{B}_d \to \pi^0 K_S$	$\lambda''_{212}\lambda''_{213}$	6.4×10^{-3}	7.2
$\overline{B}_d \to D^+ D^-$	$\lambda''_{212}\lambda''_{223}$	7.8×10^{-3}	3.2
$\overline{B}_d \to D_{CP}\pi^0(\rho^0)$	$\lambda''_{212}\lambda''_{132}$	1.6	3000
$\overline{B}_s \to \phi K_S$	$\lambda''_{212}\lambda''_{223}$	7.8×10^{-3}	25
$\overline{B}_d \to \phi \pi^0$	$\lambda''_{212}\lambda''_{223}$	7.8×10^{-3}	680
$\overline{B}_d \to \pi^+\pi^-$	$\lambda''_{112}\lambda''_{123}$	1.3×10^{-6}	1.4×10^{-3}
$\overline{B}_d \to \pi^0\pi^0$	$\lambda''_{112}\lambda''_{123}$	1.3×10^{-6}	0.01

$$\mathcal{C}^{\not B}_{ijkl} = \frac{\sqrt{2}}{4G_F}\sum_{n=1}^{3}\frac{2}{M^2_{\tilde{d}_n}}\lambda''_{ikn}\lambda''^{*}_{jln},$$

$$\mathcal{N}^{\not B}_{ijkl} = \frac{\sqrt{2}}{4G_F}\sum_{n=1}^{3}\frac{1}{M^2_{\tilde{u}_n}}\lambda''_{nik}\lambda''^{*}_{njl}. \tag{15}$$

From the above effective Lagrangian, we calculate the amplitudes for several decay modes using the factorization assumption and the results are shown in the Appendix.

By inspection of $\mathcal{N}^{\not B}_{ijkl}$, one can easily see that R_p- and B-violating couplings does not contribute B-$\overline{B}$ mixing and $B_d \to \phi K_S$ since λ''_{ijk} is antisymmetric under the exchange of the last two indices.

The present bounds on λ'' are so poor that r_D's are generally quite large except $B_d \to \pi\pi$ mode: see Table III. Large r_D means two things. One thing is that it is possible to have large CP violation completely different from the SM predictions. The other thing is that one can obtain more stringent bounds on the product combinations if the measured branching ratios of the decay modes are consistent with the SM predictions.

Note that one product combination contributes to two and more decay modes; see Table III. In this case, the differences of CP phases ϕ's of the decay modes are exactly the same as that of the SM.

In gauge-mediated supersymmetry-breaking models, λ'' are severely constrained from the proton decay [16,17]. So the contributions of R_p- and B-violating couplings to CP violating B decays can be safely ignored.

V. CONCLUSION

To conclude, we study CP-violating B decays in the minimal supersymmetric standard model with $\not R_p$. We estimate how much $\not R_p$ modifies the SM predictions for CP asymmetries in B decays within the present bounds. The effects of R_p and L violation on the ratio of the decay amplitude due to $\not R_p$ to that of the SM can differ by one or two orders of magnitudes depending on the models of the left-handed quark mixing. It is possible to disentangle the R-parity-violating effects from those of the SM and R-parity-conserving supersymmetric models within the present bounds. We also study the effects of R_p and B violation and find that the effects could be large or the contributing product combinations can be strongly constrained by the near future experiments on B mesons. The effects of R_p and B violation can be ignored in gauge-mediated supersymmetric models.

ACKNOWLEDGMENTS

We thank Y. G. Kim and P. Ko for their helpful remarks. This work was supported in part by KAIST Basic Science Research Program (J.S.L.).

APPENDIX

In this appendix, we present all decay amplitudes relevant to our analysis. We do not need to know the exact values of the form factor since they are irrelevant in the calculation of r_D for most of the cases. For the numerical calculation, we use the following values for the quark masses: $m_u = 4.2$ MeV, $m_d = 7.6$ MeV, $m_s = 122$ MeV, $m_c = 1.3$ GeV, $m_b = 4.88$ GeV, and we take $N = 3$.

1. SM

The amplitudes in the SM are calculated using the effective Hamiltonian formalism. The short and long distance QCD effects in the nonleptonic decays are separated by means of the operator product expansion. For the numerical values of the Wilson coefficients (short distance effects), we use the values in Ref. [20]. The long distance contributions of the hadronic matrix elements are calculated under the factorization approximation:

$$A(\overline{B}^0 \to \psi K_S) = \frac{G_F}{\sqrt{2}}[V_{cb}V^{*}_{cs}a_2 - V_{tb}V^{*}_{ts}(a_3+a_5+a_7+a_9)]\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\langle\psi|\overline{c}c_-|0\rangle, \tag{A1}$$

$$A(\overline{B}^0 \to \phi K_S) = -\frac{G_F}{\sqrt{2}}V_{tb}V^{*}_{ts}\left[a_3+a_4+a_5-\frac{1}{2}(a_7+a_9+a_{10})\right]\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\langle\phi|\overline{s}s_-|0\rangle, \tag{A2}$$

$$A(\overline{B}^0\to\pi^0K_S)=\frac{G_F}{\sqrt{2}}\Bigg[\left\{V_{ub}V_{us}^*a_2+\frac{3}{2}V_{tb}V_{ts}^*(a_7-a_9)\right\}\langle\pi^0|\overline{u}u_-|0\rangle\langle K_S|\overline{s}b_-|\overline{B}^0\rangle$$
$$-V_{tb}V_{ts}^*\left\{a_4-\frac{1}{2}a_{10}+\frac{m_K^2(2a_6-a_8)}{(m_d+m_s)(m_b-m_d)}\right\}\langle K_S|\overline{s}d_-|0\rangle\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\Bigg], \tag{A3}$$

$$A(\overline{B}^0\to D^+D^-)=\frac{G_F}{\sqrt{2}}\left[V_{cb}V_{cd}^*a_1-V_{tb}V_{td}^*\left\{a_4+a_{10}+\frac{2m_D^2(a_6+a_8)}{(m_c+m_d)(m_b-m_c)}\right\}\right]\langle D^+|\overline{c}b_-|\overline{B}^0\rangle\langle D^-|\overline{d}c_-|0\rangle, \tag{A4}$$

$$A(\overline{B}^0\to D_{CP}\pi^0)=\frac{G_F}{\sqrt{2}}(V_{cb}V_{ud}^*\pm V_{ub}V_{cd}^*)a_2\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A5}$$

$$A(\overline{B}^0\to D_{CP}\rho^0)=\frac{G_F}{\sqrt{2}}(V_{cb}V_{ud}^*\pm V_{ub}V_{cd}^*)a_2\langle\rho^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A6}$$

$$A(\overline{B}_s\to\phi K_S)=-\frac{G_F}{\sqrt{2}}V_{tb}V_{td}^*\left[a_3+a_4+a_5-\frac{1}{2}\{a_7+a_9+a_{10}\}+\frac{m_\phi^2(2a_6-a_8)}{2m_s(m_b-m_s)}\right]\langle K_S|\overline{d}b_-|\overline{B}_s\rangle\langle\phi|\overline{s}s_-|0\rangle, \tag{A7}$$

$$A(\overline{B}^0\to\phi\pi^0)=-\frac{G_F}{\sqrt{2}}V_{tb}V_{td}^*\left\{a_3+a_5-\frac{1}{2}(a_7+a_9)\right\}\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle\phi|\overline{s}s_-|0\rangle, \tag{A8}$$

$$A(\overline{B}^0\to\pi^+\pi^-)=\frac{G_F}{\sqrt{2}}\left[V_{ub}V_{ud}^*a_1-V_{tb}V_{td}^*\left\{a_4+a_{10}+\frac{2m_\pi^2(a_6+a_8)}{(m_u+m_d)(m_b-m_u)}\right\}\right]\langle\pi^+|\overline{u}b_-|\overline{B}^0\rangle\langle\pi^-|\overline{d}u_-|0\rangle, \tag{A9}$$

$$A(\overline{B}^0\to\pi^0\pi^0)=-\frac{2G_F}{\sqrt{2}}\left[V_{ub}V_{ud}^*a_2+V_{tb}V_{td}^*\left\{a_4+\frac{3}{2}(a_7-a_9)-\frac{1}{2}a_{10}+\frac{m_\pi^2(2a_6-a_8)}{2m_d(m_b-m_u)}\right\}\right]\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle\pi^0|\overline{u}u_-|0\rangle. \tag{A10}$$

The $\pm$ sign in the $\overline{B}^0\to D_{CP}\pi^0(\rho^0)$ decay modes corresponds to the CP-even and CP-odd eigenstates of D_{CP} and the same convention is applied to the R_p violation case. In the numerical estimation of $\overline{B}^0\to\pi^0K_S$ decay modes, we assume that $|\langle\pi^0|\overline{u}u_-|0\rangle\langle K_S|\overline{s}b_-|\overline{B}^0\rangle|\approx|\langle K_S|\overline{s}d_-|0\rangle\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle|$.

2. R_p and L violation

In this case, the running effects of the R_p-violating couplings are neglected. The hadronic matrix elements are also calculated under the factorization assumption:

$$A(\overline{B}^0\to\psi K_S)=\sum_{n,i,j}\frac{1}{M_{\tilde{l}_n}^2}\frac{1}{8N}\lambda'_{ni2}\lambda'^*_{nj3}V_{2j}V_{2i}^*\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\langle\psi|\overline{c}c_-|0\rangle, \tag{A11}$$

$$A(\overline{B}^0\to\phi K_S)=\sum_{n}\frac{1}{M_{\tilde{l}_n}^2}\frac{1}{8N}[\lambda'_{n22}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n22}]\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\langle\phi|\overline{s}s_-|0\rangle, \tag{A12}$$

$$A(\overline{B}^0\to\pi^0K_S)=\sum_{n}\frac{1}{M_{\tilde{l}_n}^2}\Bigg[\Bigg\{\frac{1}{8N}\left(\sum_{i,j}\lambda'_{ni2}\lambda'^*_{nj3}V_{1j}V_{1i}^*-\lambda'_{n12}\lambda'^*_{n13}+\lambda'_{n31}\lambda'^*_{n21}\right)$$
$$+\frac{m_\pi^2}{8m_d(m_b-m_s)}(\lambda'_{n11}\lambda'^*_{n23}-\lambda'_{n32}\lambda'^*_{n11})\Bigg\}\langle\pi^0|\overline{u}u_-|0\rangle\langle K_S|\overline{s}b_-|\overline{B}^0\rangle$$
$$+\left\{\frac{1}{8N}(\lambda'_{n11}\lambda'^*_{n23}-\lambda'_{n32}\lambda'^*_{n11})-\frac{m_{K_S}^2}{4(m_b-m_d)(m_d+m_s)}(\lambda'_{n12}\lambda'^*_{n13}-\lambda'_{n31}\lambda'^*_{n21})\right\}$$

$$\times\langle K_S|\overline{s}d_-|0\rangle\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\Bigg], \tag{A13}$$

$$A(\overline{B}^0\to D^+D^-)=\sum_{n,i,j}\frac{1}{M^2_{\tilde{l}_n}}\frac{m^2_{D^-}}{4(m_d+m_c)(m_b-m_c)}\lambda'_{ni1}\lambda'^*_{nj3}V_{2j}V^*_{2i}\langle D^+|\overline{c}b_-|\overline{B}^0\rangle\langle D^-|\overline{d}c_-|0\rangle, \tag{A14}$$

$$A(\overline{B}^0\to D_{CP}\pi^0)=\sum_{n,i,j}\frac{1}{M^2_{\tilde{l}_n}}\lambda'_{ni1}\lambda'^*_{nj3}\frac{1}{8N}[V_{2j}V^*_{1i}\pm V_{1j}V^*_{2i}]\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A15}$$

$$A(\overline{B}^0\to D_{CP}\rho^0)=-\sum_{n,i,j}\frac{1}{M^2_{\tilde{l}_n}}\lambda'_{ni1}\lambda'^*_{nj3}\frac{1}{8N}[V_{2j}V^*_{1i}\pm V_{1j}V^*_{2i}]\langle\rho^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A16}$$

$$\begin{aligned}A(\overline{B}_s\to\phi K_S)=-\sum_n\frac{1}{M^2_{\tilde{l}_n}}\Bigg[\Bigg\{&\frac{1}{8N}(\lambda'_{n12}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n21}+\lambda'_{n22}\lambda'^*_{n13}+\lambda'_{n31}\lambda'^*_{n22})\\&+\frac{m^2_{K_S}}{4(m_s+m_d)(m_s+m_b)}(\lambda'_{n12}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n21}+\lambda'_{n21}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n12})\Bigg\}\\&\times\langle\phi|\overline{s}b_-|\overline{B}_s\rangle\langle K_S|\overline{d}s_-|0\rangle-\frac{1}{8N}(\lambda'_{n21}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n12})\langle K_S|\overline{d}b_-|\overline{B}_s\rangle\langle\phi|\overline{s}s_-|0\rangle\Bigg],\end{aligned} \tag{A17}$$

$$A(\overline{B}^0\to\phi\pi^0)=\sum_n\frac{1}{M^2_{\tilde{l}_n}}\frac{1}{8N}(\lambda'_{n21}\lambda'^*_{n23}+\lambda'_{n32}\lambda'^*_{n12})\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle\phi|\overline{s}s_-|0\rangle, \tag{A18}$$

$$A(\overline{B}^0\to\pi^+\pi^-)=-\sum_{n,i,j}\frac{1}{M^2_{\tilde{l}_n}}\frac{m^2_{\pi^-}}{4(m_d+m_u)(m_b-m_u)}\lambda'_{ni1}\lambda'^*_{nj3}V_{1j}V^*_{1i}\langle\pi^+|\overline{u}b_-|\overline{B}^0\rangle\langle\pi^-|\overline{d}u_-|0\rangle, \tag{A19}$$

$$\begin{aligned}A(\overline{B}^0\to\pi^0\pi^0)=\sum_n\frac{1}{M^2_{\tilde{l}_n}}\Bigg[&\sum_{i,j}\frac{1}{4N}\lambda'_{ni1}\lambda'^*_{nj3}V_{1j}V^*_{1i}-\Bigg\{\frac{1}{4N}-\frac{m^2_{\pi^0}}{4m_d(m_b-m_d)}\Bigg\}(\lambda'_{n11}\lambda'^*_{n13}-\lambda'_{n31}\lambda'^*_{n11})\Bigg]\\&\times\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle\pi^0|\overline{u}u_-|0\rangle.\end{aligned} \tag{A20}$$

In $\overline{B}^0\to\pi^0K_S$ and $\overline{B}^0\to\phi K_S$ modes, we assume that the magnitudes of two form factors are approximately same.

3. R_p and B violation

The decay amplitudes for R_p and B violation are calculated in the similar way as the case of R_p and L violation:

$$A(\overline{B}^0\to\psi K_S)=-\sum_n\frac{1}{2M^2_{\tilde{d}_n}}\left(1-\frac{1}{N}\right)\lambda''_{22n}\lambda''^*_{23n}\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\langle\psi|\overline{c}c_-|0\rangle, \tag{A21}$$

$$A(\overline{B}^0\to\phi K_S)=0, \tag{A22}$$

$$\begin{aligned}A(\overline{B}^0\to\pi^0K_S)=\sum_n\Bigg[&\Bigg\{\frac{1}{2M^2_{\tilde{d}_n}}\lambda''_{12n}\lambda''^*_{13n}-\frac{1}{2M^2_{\tilde{u}_n}}\lambda''_{n12}\lambda''^*_{n13}\Bigg\}\left(1-\frac{1}{N}\right)\langle\pi^0|\overline{u}u_-|0\rangle\langle K_S|\overline{s}b_-|\overline{B}^0\rangle\\&-\frac{1}{2M^2_{\tilde{u}_n}}\left(1-\frac{1}{N}\right)\lambda''_{n12}\lambda''^*_{n13}\langle K_S|\overline{s}d_-|0\rangle\langle\pi^0|\overline{d}b_-|\overline{B}^0\rangle\Bigg],\end{aligned} \tag{A23}$$

$$A(\overline{B}^0 \to D^+ D^-) = -\sum_n \frac{1}{2M^2_{\tilde{d}_n}} \left(1-\frac{1}{N}\right) \lambda''_{21n}\lambda''^{*}_{23n} \langle D^+|\overline{c}b_-|\overline{B}^0\rangle\langle D^-|\overline{d}c_-|0\rangle, \tag{A24}$$

$$A(\overline{B}^0 \to D_{CP}\pi^0) = \sum_n \frac{1}{2M^2_{\tilde{d}_n}} \left(1-\frac{1}{N}\right) [\lambda''_{21n}\lambda''^{*}_{13n} \pm \lambda''_{11n}\lambda''^{*}_{23n}] \langle \pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A25}$$

$$A(\overline{B}^0 \to D_{CP}\rho^0) = -\sum_n \frac{1}{2M^2_{\tilde{d}_n}} \left(1-\frac{1}{N}\right) [\lambda''_{21n}\lambda''^{*}_{13n} \pm \lambda''_{11n}\lambda''^{*}_{23n}] \langle \rho^0|\overline{d}b_-|\overline{B}^0\rangle\langle D_{CP}|\overline{c}u_-|0\rangle, \tag{A26}$$

$$A(\overline{B}_s \to \phi K_S) = -\sum_n \frac{1}{2M^2_{\tilde{u}_n}} \left(1-\frac{1}{N}\right) \lambda''_{n12}\lambda''^{*}_{n23} [\langle \phi|\overline{s}b_-|\overline{B}_s\rangle\langle K_S|\overline{d}s_-|0\rangle - \langle K_S|\overline{d}b_-|\overline{B}_s\rangle\langle \phi|\overline{s}s_-|0\rangle], \tag{A27}$$

$$A(\overline{B}^0 \to \phi\pi^0) = \sum_n \frac{1}{2M^2_{\tilde{u}_n}} \left(1-\frac{1}{N}\right) \lambda''_{n12}\lambda''^{*}_{n23} \langle \pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle \phi|\overline{s}s_-|0\rangle, \tag{A28}$$

$$A(\overline{B}^0 \to \pi^+\pi^-) = -\sum_n \frac{1}{2M^2_{\tilde{d}_n}} \left(1-\frac{1}{N}\right) \lambda''_{11n}\lambda''^{*}_{13n} \langle \pi^+|\overline{u}b_-|\overline{B}^0\rangle\langle \pi^-|\overline{d}u_-|0\rangle, \tag{A29}$$

$$A(\overline{B}^0 \to \pi^0\pi^0) = \sum_n \frac{1}{M^2_{\tilde{d}_n}} \left(1-\frac{1}{N}\right) \lambda''_{11n}\lambda''^{*}_{13n} \langle \pi^0|\overline{d}b_-|\overline{B}^0\rangle\langle \pi^0|\overline{u}u_-|0\rangle. \tag{A30}$$

In the $\overline{B}_s \to \phi K_S$ decay mode, we assume [21]

$$\frac{\langle K_S|\overline{d}b_-|\overline{B}_s\rangle\langle \phi|\overline{s}s_-|0\rangle - \langle \phi|\overline{s}b_-|\overline{B}_s\rangle\langle K_S|\overline{d}s_-|0\rangle}{\langle K_S|\overline{d}b_-|\overline{B}_s\rangle\langle \phi|\overline{s}s_-|0\rangle} \approx \mathcal{O}(1).$$

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