Exploring Flavor Structure of Supersymmetry Breaking

at B factories *

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Abstract

We investigate flavor physics at present and future B factories in order to distinguish supersymmetric models. We evaluate CP asymmetries in various B decay modes, $\Delta m_{B_d}$, $\Delta m_{B_s}$, and $\varepsilon_K$ in three supersymmetric models, i.e. the minimal supergravity, the SU(5) SUSY GUT with right handed neutrinos, and a supersymmetric model with U(2) flavor symmetry. The allowed regions of $\Delta m_{B_s}/\Delta m_{B_d}$ and CP asymmetries in $B \rightarrow J/\psi K_S$ and $b \rightarrow s \gamma$ are different for the three models so that it is possible to distinguish the three models by precise determinations of these observables in near future experiments.

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I. INTRODUCTION

CP violation in $B$ system has been established by measurements of Belle experiment at KEK\[1\] and BaBar experiment at SLAC\[2\]. In the standard model(SM), the phenomenon of CP violation originates from Kobayashi-Maskawa mechanism\[3\] and the experimental results are consistent with the predictions of the SM. In near future, it is expected that measurements of CP violation and rare decay processes will be improved at the asymmetric $B$ factories and that the magnitude of $B_0^0-\bar{B}_0^0$ mixing will be determined at the Fermilab Tevatron experiments\[4\]. Within a few years, we will be able to know whether or not significant effects of new physics reside in the $B$ systems.

Supersymmetry(SUSY) is one of the most attractive candidates of physics beyond the SM. SUSY gives a justification to the electroweak scale, which is much smaller than the Planck scale. In SUSY models, there exist some features: (i) the gauge coupling constants can be unified, (ii) the existence of light Higgs boson is predicted, (iii) there are superpartners of the SM particles, and so on.

Mass matrices of superpartners of quarks and leptons are new sources of flavor mixing and CP violation. These mass matrices are determined from SUSY breaking terms in the Lagrangian, and these terms reflect the SUSY breaking mechanism and interactions that present between the scale of the SUSY breaking and the electroweak scale. For general soft SUSY breaking, if the squark and slepton masses are below a few TeV, the experimental data of $\varepsilon_K$ which is related to the CP violation in $K^0-\bar{K}^0$ mixing and $\mu \to e\gamma$ require strong degeneracy between the first- and second-family squarks and sleptons. In order to realize this degeneracy, many flavor models are considered and these models predict different flavor structures. Therefore if SUSY particles are discovered at LHC and/or a linear collider experiment, $B$ physics is expected to play an important role in studying the flavor structure of SUSY models.

Now we address the following question: Can we distinguish SUSY models by measurements at $B$ factories? In order to answer this question, we investigate SUSY effects on $B$ physics in three different SUSY models, namely (i) the minimal supergravity(mSUGRA) model, (ii) the SU(5) SUSY grand unified theory (GUT) with right-handed neutrinos\[5\], and (iii) a supersymmetric model with U(2) flavor symmetry\[6, 7\]. In our recent paper\[8\], we focus on the new physics search through the consistency check of the unitarity triangle.
and we evaluate SUSY effects on CP asymmetries in $B \rightarrow J/\psi K_S$, $\Delta m_{B_s}$, $\Delta m_{B_d}$, $\varepsilon_K$, and $\phi_3 \equiv \arg(-V^*_{ub}V_{ud}/V^*_{cb}V_{cd})$. In this talk, besides these observables, we also evaluate both direct and mixing CP asymmetries in $B \rightarrow X_s \gamma$.

II. MODELS

Here, we give a brief description of models. A detailed discussion of these models can be found in Ref. [8].

A. The minimal supergravity model

In the mSUGRA, SUSY is spontaneously broken in the hidden sector and the hidden sector of the theory communicates with our MSSM sector only through the gravitational interaction. The soft breaking terms are induced through the gravitational interaction and the structure of soft breaking terms have no new flavor mixing at the scale where the soft breaking terms are induced.

In this model, the source of flavor mixing is only CKM mixing matrix. The universality of the squark sector is lost due to radiative corrections induced by the CKM mixing. We use renormalization group(RG) equations in order to trace these radiative corrections and determine the soft breaking terms at the electroweak scale.

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

The measurements of three gauge coupling constants support the idea of the supersymmetric grand unification. Furthermore, recent results of neutrino oscillation experiments suggest the existence of finite mass of neutrinos. In order to explain these points, the SU(5) SUSY GUT with right-handed neutrinos is considered [5].

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 have two sources of flavor mixing. One is CKM matrix as in the case of the mSUGRA. Another is Maki-Nakagawa-Sakata matrix [4], which is the mixing matrix of the lepton sector. A large flavor mixing in the neutrino sector can
affect the squark mixing in the right-handed down type sector through GUT interactions.

C. A model with U(2) flavor symmetry

Instead of assuming the universality of sfermion mass matrices, it is possible to solve the flavor problem of SUSY by introducing some flavor symmetry. U(2) flavor symmetry is one of such symmetries. We use 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 while the third generation and the Higgs supermultiplets are singlet under the U(2).

In order to obtain the correct structure of Yukawa couplings, we assume that the breaking pattern of the U(2) is

$$U(2) \rightarrow U(1) \rightarrow \mathbb{1} (\text{no symmetry}).$$  \hspace{1cm} (1)

With this U(2) breaking, we obtain the quark Yukawa couplings $f_Q$ and the squark mass matrices $m_X^2$:

$$(f_Q^{ij}) = y_Q \begin{pmatrix} 0 & a_Q \epsilon' & 0 \\ -a_Q \epsilon' & d_Q \epsilon & b_Q \epsilon \\ 0 & c_Q \epsilon & 1 \end{pmatrix}, \quad Q = U, D, \hspace{1cm} (2)$$

$$m_X^2 = m_0^X \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 + r_{23}^X \epsilon^2 & r_{23}^X \epsilon \\ 0 & r_{23}^X \epsilon & r_{33}^X \epsilon \end{pmatrix}, \quad X = Q, U, D, \hspace{1cm} (3)$$

where $\epsilon \simeq \lambda^2$ and $\epsilon' \simeq \lambda^3$ are parameters of the U(2) and U(1) symmetry breakings respectively, and $y_Q$’s, $a_Q$’s, $b_Q$’s, $c_Q$’s, $d_Q$’s, and $r^X$’s are dimensionless constant parameters of $O(1)$.

In the mass matrices of sfermions in this model, the degeneracy between masses of the first and the second generation is naturally realized, while mass of the third generation may be separated from the others and there exist flavor mixing between the 2nd and the 3rd generation of sfermions. This is new source of flavor mixing besides CKM mixing matrix.
III. NUMERICAL ANALYSIS

A. Parameters

The parameters and experimental constraints used in our calculation are the same as those in Ref. [8] except for the analysis of CP asymmetries in $b \rightarrow s \gamma$. In the analysis of CP asymmetries in $b \rightarrow s \gamma$, we introduce new CP violating phases on the tri-linear scalar couplings($A$-terms).

B. Numerical results

First, we discuss SUSY contributions to $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$, $\varepsilon_K$, and $\phi_3$. We vary $|V_{ub}/V_{cb}|$ and $\phi_3$ and impose experimental constraints such as $B(b \rightarrow s \gamma)$, $B(\mu \rightarrow e \gamma)$, the measured values of $\varepsilon_K$ and $\Delta m_{B_d}$, and the lower bound of $\Delta m_{B_s}$. In Fig. 1, we show possible values of $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$, $\Delta m_{B_s}/\Delta m_{B_d}$, and $\phi_3$ for the parameter sets which satisfy the constraints.

In the mSUGRA, the deviations from the SM values are not significant. Because there are at most 10% deviations in $\varepsilon_K$ while $\Delta m_{B_s}$, $\Delta m_{B_d}$, and $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$ are almost the same as the values of the SM, it seems that there are at most 10% deviations in both the $(A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S), \Delta m_{B_s}/\Delta m_{B_d})$ plane and the $(A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S), \phi_3)$ plane.

In the SU(5) SUSY GUT with right-handed neutrinos, though we can see the deviation of order one in each observable, all the allowed points lie between the lines corresponding to the SM values with $|V_{ub}/V_{cb}| = 0.08$ and 0.10. This is due to the fact that there exist significant SUSY contribution only to the $K^0 - \bar{K}^0$ mixing, not to the $B^0 - \bar{B}^0$ mixing. There can be SUSY contribution of order one to $\varepsilon_K$, while $\Delta m_{B_s}$, $\Delta m_{B_d}$, and $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$ are not affected by SUSY.

In the U(2) model, there are SUSY contributions to both the $K^0 - \bar{K}^0$ mixing and the $B^0 - \bar{B}^0$ mixing. In addition to the huge SUSY contribution to $\varepsilon_K$, there are correction of order one to $\Delta m_{B_s}$ and $\Delta m_{B_d}$. Therefore the $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$, and $\phi_3$ can be considerably different from the SM values.

Here we discuss future prospects of new physics search in $B$ physics. It is expected that $A_{CP}^{\text{mix}}(B \rightarrow J/\psi K_S)$ and $\Delta m_{B_s}/\Delta m_{B_d}$ will be precisely measured in near future at the $B$ factories and Tevatron experiments. As an illustration, we consider two cases that
FIG. 1: Scatter plots in the planes ($A_{\text{mix}}^{\text{CP}}(B \rightarrow J/\psi K_S)$, $\Delta m_{B_s}/\Delta m_{B_d}$) and ($\phi_3$, $\Delta m_{B_s}/\Delta m_{B_d}$) for three SUSY models. Solid curves show the SM values with fixed $|V_{ub}/V_{cb}| = 0.08, 0.09$ and $0.10$.

$\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{\text{mix}}^{\text{CP}}(B \rightarrow J/\psi K_S)$ are precisely determined at future $B$ experiments as

(a) $\Delta m_{B_s}/\Delta m_{B_d} = 35 \times (1 \pm 0.05)$, $A_{\text{mix}}^{\text{CP}}(B \rightarrow J/\psi K_S) = 0.75 \pm 0.02$,
(b) $\Delta m_{B_s}/\Delta m_{B_d} = 55 \times (1 \pm 0.05)$, $A_{\text{mix}}^{\text{CP}}(B \rightarrow J/\psi K_S) = 0.75 \pm 0.02$.

(a) corresponds to the case where $A_{\text{mix}}^{\text{CP}}(B \rightarrow J/\psi K_S)$, and $\Delta m_{B_s}/\Delta m_{B_d}$ are consistent with the SM. (b) is the case where there is some inconsistency among the three observables within the SM. In Fig. 2, we present the possible region of $\phi_3$ in the cases (a) and (b) for the three models.

For the case (a), $\phi_3 = 60^\circ - 65^\circ$ in the SM. The values of $\phi_3$ in the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos are similar to the value of the SM. On the other hand, in the U(2) model, the $\phi_3$ value may be different from the value in the SM.
FIG. 2: Possible regions of $\phi_3$ as a function of the gluino mass.

For the case (b), as well as the SM, the mSUGRA is excluded. In the other two models, there exist the allowed regions of $\phi_3$ value.

Secondly, we evaluate the direct CP asymmetry $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ in the inclusive decays $B \to X_s \gamma$ and the mixing induced CP asymmetry $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ in the exclusive decays $B^0 \to M_s \gamma$ where $M_s$ denotes a CP eigen state which includes a strange quark such as $K^*$ and $K_1$. It is expected that $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ would be a clean signal of new physics\cite{10, 11},
because in the SM it can be calculated precisely and is found to be about 0.5\%\[1]. Though the value of $A_{\text{mix}}^{\text{CP}}(B \to M_s \gamma)$ in the SM is at a level of 1\%\[2], this value may significantly change with new physics contributions\[3].

In Fig. 3, we show possible regions of $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ and the electric dipole moment (EDM) of the neutron with its experimental bound $|d_n| < 0.63 \times 10^{-25} \text{e} \cdot \text{cm}$. The values of EDM of the neutron become larger as the deviation of $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ increases. This constraint of EDM is so strong that in the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos, the value of $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ is about 0.5\% which is predicted in the SM for the allowed value of EDM of the neutron. In the U(2) model, $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ can be as large as a few percents even under the constraint from the EDM.

The allowed region of $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ is shown as a function of the lightest stop mass in Fig. 4. In the U(2) model, $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ can be as large as a few percent even if the mass of the lightest stop is as large as 2.5TeV, while in the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos the value of $A_{\text{CP}}^{\text{dir}}(B \to X_s \gamma)$ is about 0.5\% in all range of the lightest stop mass.

In Fig. 5, the possible regions of $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ are plotted as a function of the lightest stop mass. In the mSUGRA, $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ is almost the same as the value of the SM. In the SU(5) SUSY GUT with right-handed neutrinos, for the region where the lightest stop mass $m(\tilde{t}_1)$ is smaller than 1TeV, we find that $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ is different from the value of the SM and becomes at most about 10\%. In the U(2) model, $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ can be as large as 0.5 for the range of $m(\tilde{t}_1) < 1\text{TeV}$. Even in the case of $m(\tilde{t}_1) > 1\text{TeV}$, $A_{\text{CP}}^{\text{mix}}(B \to M_s \gamma)$ in the U(2) model can be as large as 0.2.

**IV. SUMMARY**

In order to distinguish SUSY models by measurements at B factories, we have evaluated SUSY contributions to several observables in B physics. We use three typical SUSY models, namely, mSUGRA, the SU(5) SUSY GUT with right-handed neutrinos, and the U(2) model.

First we have considered $\Delta m_{B_s}$, $\Delta m_{B_d}$, $A_{\text{CP}}^{\text{mix}}(B \to J/\psi K_S)$, $\varepsilon_K$, and $\phi_3$. In the mSUGRA, the deviations from the SM values exist only in $\varepsilon_K$ and is at most 10\% and $\Delta m_{B_s}$, $\Delta m_{B_d}$, $A_{\text{CP}}^{\text{mix}}(B \to J/\psi K_S)$, and $\phi_3$ are almost the same as in the SM. In the SU(5) SUSY GUT with right-handed neutrinos, there is deviation of order one in $\varepsilon_K$ from the
FIG. 3: Scatter plots in the plane of $A_{\text{dir}}^{\text{CP}}(B \to X_s \gamma)$ and the electric dipole moment of the neutron $|d_n|$ for three SUSY models. The gray points are excluded by the experimental constraint of $|d_n|$.

FIG. 4: Possible regions of $A_{\text{dir}}^{\text{CP}}(B \to X_s \gamma)$ as a function of the lightest stop mass.

value of the SM. As well as in the mSUGRA, $\Delta m_{B_s}$, $\Delta m_{B_d}$, $A_{\text{mix}}^{\text{CP}}(B \to J/\psi K_S)$, and $\phi_3$ are not affected by SUSY contributions. In the U(2) model, there are so large contribution to $\varepsilon_K$ that the value of $\varepsilon_K$ can be as ten times large as the value of the SM. In addition, the SUSY contributions affect not only $\varepsilon_K$ but also $\Delta m_{B_s}$, $\Delta m_{B_d}$, $A_{\text{mix}}^{\text{CP}}(B \to J/\psi K_S)$, and $\phi_3$. The deviations of $\Delta m_{B_s}$, $\Delta m_{B_d}$ from the values of the SM can be order one.

In the case that the two observables $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{\text{mix}}^{\text{CP}}(B \to J/\psi K_S)$ are precisely determined at the $B$ factories in near future, it may be possible to distinguish the different SUSY models by measuring $\phi_3$ at the $B$ factories and Tevatron experiments.
FIG. 5: Possible region of $A^\text{mix}_{\text{CP}}(B \to M_s \gamma)$ as a function of the lightest stop mass.

Secondly, we have investigated SUSY contributions to $A^\text{dir}_{\text{CP}}(B \to X_s \gamma)$ and $A^\text{mix}_{\text{CP}}(B \to M_s \gamma)$. Owing to the constraint from the EDM of the neutron, the values of $A^\text{dir}_{\text{CP}}(B \to X_s \gamma)$ in the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos are almost consistent with the value expected in the SM. On the other hand, in the U(2) model, $A^\text{dir}_{\text{CP}}(B \to X_s \gamma)$ can be as large as a few percent which is ten times larger than the value in the SM.

In the mSUGRA, $A^\text{mix}_{\text{CP}}(B \to M_s \gamma)$ is almost the same as in the SM for all range of the lightest stop mass. In the SU(5) SUSY GUT with right-handed neutrinos, $A^\text{mix}_{\text{CP}}(B \to M_s \gamma)$ can be as large as 10% if the lightest stop mass is smaller than 1TeV. We have shown that in the U(2) model, $A^\text{mix}_{\text{CP}}(B \to M_s \gamma)$ can be $\approx 0.5$ in the parameter region where the lightest stop mass is smaller than 1TeV. Even in the case that the lightest stop mass is larger than 1TeV, a 20% asymmetry in $B \to M_s \gamma$ is possible.

In conclusion, as we have illustrated with three specific models, SUSY models with different flavor structures exhibit different patterns of the deviations from the SM in the $B$ physics. Therefore experiments at $e^+e^-$ $B$ factories and hadron machines are very important to explore the flavor structure of SUSY breaking.

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