SUSY and CP Violation

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Abstract

Flavor changing neutral current and CP violating processes are discussed in the minimal supergravity model. The constraint on charged Higgs mass from the new measurement of the inclusive branching ratio of the $b \to s \gamma$ process is obtained. The $B_d^0 - \bar{B}_d^0$ mixing parameter ($x_d$) and the CP violating parameter in the $K^0 - \bar{K}^0$ mixing ($\epsilon_K$) are calculated in this model and it is shown that these parameters can be enhanced by $10\%-20\%$ compared to the prediction within the standard model. Impacts on new physics search at B factories are also discussed.
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ABSTRACT

Flavor changing neutral current and CP violating processes are discussed in the minimal supergravity model. The constraint on charged Higgs mass from the new measurement of the inclusive branching ratio of the $b \to s \gamma$ process is obtained. The $B^0_d - \bar{B}^0_d$ mixing parameter ($x_d$) and the CP violating parameter in the $K^0 - \bar{K}^0$ mixing ($\epsilon_K$) are calculated in this model and it is shown that these parameters can be enhanced by $10\% \sim 20\%$ compared to the prediction within the standard model. Impacts on new physics search at B factories are also discussed.

1. Introduction

Although nature of gauge interactions between fermions and gauge bosons has been getting clearer in recent years, other aspects of the standard model (SM) such as origin of CP violation and mechanism of electroweak symmetry breaking have not yet been understood experimentally. Main purpose of B factory projects at KEK and SLAC is to measure CP violating asymmetries in B decays and to see whether various CP violating processes are consistently explained by a single phase of the Cabbibo-Kobayashi-Maskawa (CKM) matrix. If that turns out to be the case, one of important aspects of the SM will be established experimentally, on the other hand, if not, we will have a clear evidence of physics beyond the SM.

One of promising candidates of the physics beyond the SM is a supersymmetric (SUSY) extension. It is then important to know how the SUSY effects can appear in physics on B decays. Although the original motivation of the SUSY models is to give a possible explanation to the hierarchy problem in the Higgs sector of the SM, their flavor sector also has unique features. Firstly, any viable SUSY model contains at least two Higgs doublets, therefore a physical charged Higgs is an inevitable consequence of the SUSY SM. This Higgs can affect flavor changing neutral current (FCNC) processes through loop diagrams. Moreover, squark mass matrices can be new sources of flavor mixing. Since these squark mass matrices are in part determined from SUSY breaking parameters, the investigation of FCNC and CP violating processes could lead us to knowledges about the SUSY breaking mechanism.

In this talk I will discuss how SUSY effects can appear in physics on B decays. For this purpose, we should distinguish two scenarios on the flavor mixing in SUSY models. The first one is the “minimal flavor mixing case” in which the origin of the flavor mixing and the CP violation lies in the ordinary Yukawa coupling
constants in superpotential. The minimal supergravity model is classified as an example of this type, where the SUSY breaking parameters are real and common for all flavors at the grand unification scale. The other corresponds to the general flavor mixing case where the flavor mixing in the squark sector is not simply related to that in the quark sector and CP violations could arise from many new physical complex phases. In the latter case phenomenological constraints from the $K^0 - \bar{K}^0$ mixing and the neutron’s electric dipole moment become important. Here we only consider the minimal case, especially a model based on the minimal supergravity model. We first consider the constraints on parameters obtained from the recent measurement of the inclusive $b \to s\gamma$ branching ratio [2]. Although there have been many works [3]-[17] on the SUSY contributions to the $b \to s\gamma$ process, both in the minimal supersymmetric standard model (MSSM) and in the minimal supergravity model, we re-evaluate the branching ratio and present the result as a constraint on charged Higgs mass from this process [18]. Next, we calculate the $B^0_d - \bar{B}^0_d$ mixing parameter ($\epsilon_d$) and the CP violating parameter in the $K^0 - \bar{K}^0$ mixing ($\epsilon_K$) in the SUSY model. Here also there have been many previous works [1, 3, 19]. We have updated the analysis [20] using the new experimental input on the top quark mass [21] and the constraint from the measured inclusive $b \to s\gamma$ branching ratio [2]. Presently, these processes do not put strong constraints on the SUSY parameter space once other phenomenological constraints are taken into account. However, when the measurements of CP asymmetries at future B factory experiments provide new information on the CKM matrix there is a good chance that some SUSY effects are extracted from combined analysis of $\epsilon_d$, $\epsilon_K$ and the CP asymmetries in B decays.

2. Minimal Supergravity Model

We consider here the minimal supersymmetric standard model (MSSM) [22]. Each particle of the SM has its superpartner. Corresponding to gauge bosons, quarks, leptons and Higgs boson, gauginos, squarks, sleptons and higgsino have to be introduced. These particles can be classified in five sectors, namely, three ordinary sectors (quark-lepton, gauge field and Higgs sectors) and two sectors of superpartners (squark-slepton and chargino-neutralino-gluino sectors). Here the charginos and neutralinos are combinations of the gauginos and higgsinos.

The Higgs sector contains two Higgs doublets. One of them, denoted by $H_1$, couples to the down-type quarks and the leptons and the other, denoted by $H_2$, to the up-type quarks. There are five physical particle states, i.e., two neutral scalars and one neutral pseudo scalar and one pair of charged Higgs. The masses and mixings of these particles are parametrized by the pseudo scalar mass ($m_A$) and the ratio of the two vacuum expectation values, $\tan \beta = \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}$, where $H_1^0$ and $H_2^0$ are neutral components of the Higgs fields. In addition to these parameters the top and stop masses enter in the formulas of the various Higgs masses through one loop corrections to the Higgs potential [23].

For discussions on FCNC processes the existence of the charged Higgs is
important. At the tree level, the charged Higgs and the pseudo scalar masses are related as follows:

\[ m_{H^\pm}^2 = m_W^2 + m_A^2, \]  

(1)

where \( m_{H^\pm} \) and \( m_W \) are masses of the charged Higgs and the W boson. This relation remains to be in a good approximation even if the one loop corrections to the Higgs potential are taken into account\(^{24}\). Notice that properties of the lightest neutral scalar Higgs are almost the same as those of the SM Higgs if the charged Higgs mass is much larger than 200 GeV. On the other hand, the investigation of the lightest Higgs alone could provide us an evidence that the Higgs sector is different from the simplest one Higgs doublet model in the case that the charged Higgs is relatively light. We will see later that the FCNC and CP violating processes are especially sensitive to the parameter region with the light charged Higgs.

The chargino-neutralino sector consists of two charged Dirac fermions and four neutral Majorana fermions. Their mass matrices depend on SUSY breaking gaugino masses (\( M_1, M_2 \)) and a higgsino mass parameter (\( \mu \)) as well as the W and Z boson masses and \( \tan \beta \). The chargino mass matrix is given by

\[
M_C = \begin{pmatrix}
M_2 & \sqrt{2}m_W \sin \beta \\
\sqrt{2}m_W \cos \beta & \mu
\end{pmatrix},
\]

(2)

where the first row and column corresponds to the wino (a superpartner to the W gauge boson) states and the second row and column to the higgsino states. From this mass matrix we can see that the lightest chargino behaves like a pure wino (or higgsino) in the limit of \( M_2 \ll \mu \) \((M_2 \gg \mu)\).

In the squark sector one complex field must be introduced for each Weyl fermion in the quark sector. Since there are three generations of quarks the up- and down-type squark mass matrices are 6x6 matrices including left-right squark mixing terms. These squark mass matrices depend on SUSY soft breaking parameters. A general form in the Lagrangian contributing to the matrices is given by

\[
\mathcal{L}_{soft} = -m_{Q_{ij}}^2 \tilde{q}_i \tilde{q}_j - m_{d_{ij}}^2 \tilde{d}_i \tilde{d}_j - m_{u_{ij}}^2 \tilde{u}_i \tilde{u}_j - \tilde{u}_R^* \left( m_u A_u \right)_{ij} \tilde{u}_L - \tilde{d}_R^* \left( m_d A_d \right)_{ij} \tilde{d}_L + c.c..
\]

(3)

Although these soft breaking terms contain many free parameters in general SUSY SM, their forms are strongly constrained from FCNC processes. Especially, the smallness of the \( K^0 - \bar{K}^0 \) mixing requires that the masses of squarks with the same gauge quantum numbers should be highly degenerate for the first and second generations if these masses are less than a few TeV\(^{23}\). Whether this degeneracy is obtained without fine-tuning depends on how these SUSY soft breaking terms are generated.

In the minimal supergravity model, soft breaking terms are supposed to arise from gravity interactions with a sector where local SUSY is spontaneously broken. We can assume that this sector, called a hidden sector, is flavor-blind. In such a case
the ordinary Yukawa coupling constants in the superpotential are a unique source of the flavor mixing. In this minimal model the soft breaking terms are given as,

\[ \mathcal{L}_{\text{soft}} = -m^2_0 \sum_i |\phi_i|^2 - A(H_2 \tilde{u}^c f_u \tilde{q}_L + H_1 \tilde{d}^c f_d \tilde{q}_L) + \text{c.c.}, \] (4)

where \( m^2_0 \) is a common SUSY breaking mass for all scalar fields and \( A \) is a common trilinear coupling parameter. \( f_u \) and \( f_d \) are the ordinary Yukawa coupling constant matrices.

These parameters are supposed to be generated at the GUT or Planck scale. The squark mass matrices at the weak scale are calculated by solving renormalization group equations for soft breaking and other relevant parameters. As a result, the following general conclusions can be drawn:

1) The squarks in the first and second generations with the same quantum numbers remain highly degenerate at the weak scale. Therefore, the constraint from the \( K^0 - \bar{K}^0 \) mixing is naturally satisfied. On the other hand, the squarks in the third generation can be substantially lighter than other squarks because renormalization effects due to the large top Yukawa coupling constant make the stop or left-sbottom mass lighter at the low energy scale [26].

2) The electroweak symmetry breaking can be induced by the renormalization effects due to the large top Yukawa coupling constant starting from the assumption that all the scalar fields have a common SUSY breaking mass. This is called radiative electroweak symmetry breaking scenario [27].

3) Although squarks and quarks are simultaneously diagonalized at the GUT scale, the renormalization from the GUT to the weak scale can induce a mismatch between two mass matrices. This will cause flavor changing interactions even in gluino(or neutralino)-quark-squark couplings [26].

We have solved the renormalization group equations numerically including full complex Yukawa coupling matrices and calculated the squark mass matrices at the weak scale. In the present model, the squark’s flavor mixing is completely determined by the CKM matrix and other flavor-blind parameters. We have also found that in a very good approximation the complex phase of the squark’s mixing matrix is the same as that of the corresponding element in the CKM matrix. As a result, the \( B^0 - \bar{B}^0 \) box diagrams both for the SM contributions and for the SUSY ones have the same complex phase. Previously, this was pointed out using an approximate solution of the renormalization group equations [1]. Our numerical calculation has confirmed the assertion.

Although the \( K^0 - \bar{K}^0 \) mixing does not cause any serious problem once we take the minimal flavor mixing scenario, the FCNC processes including the third generation might be substantially influenced by the presence of SUSY particles. We
will discuss such processes, i.e. $b \to s \gamma$, $B^0_d - \bar{B}^0_d$ mixing, and $\epsilon_K$ in the followings.

### 3. $b \to s \gamma$ Process in the Minimal Supergravity Model

Recently, the CLEO collaboration reported the inclusive branching ratio of the radiative $b$ decay, $\text{Br}(b \to s \gamma) = (2.32 \pm 0.51 \pm 0.29 \pm 0.32) \times 10^{-4}$ [2]. This value is consistent with the theoretical prediction within the SM which is $(2 \sim 3) \times 10^{-4}$ [28, 29, 30]. In the SM this process is induced by the electroweak one-loop diagram called a penguin diagram. If new physics beyond the SM exists, there may be extra contributions to the $b \to s \gamma$ amplitude. In fact, for a certain type of two Higgs doublet model (THDM) called Model II the charged Higgs mass less than 260 GeV is excluded by this process [2, 28, 31]. In SUSY models, SUSY particles also contribute to the $b \to s \gamma$ amplitude in addition to the SM particles and the charged Higgs. New contributions are loop diagrams from (i) chargino and up-type squarks, (ii) gluino and down-type squarks and (iii) neutralino and down-type squarks. Although the charged Higgs contribution is the same as that of the Model II THDM, and therefore only constructively interferes with the SM contribution, the amplitude due to the SUSY particle loops can have either sign depending on parameters in the SUSY Lagrangian. Therefore, no general bound on the charged Higgs mass is obtained unlike the simple Model II THDM.

We now consider the $b \to s \gamma$ branching ratio in the context of the minimal supergravity model and present the results as the charged Higgs mass bounds [18]. In this case number of free parameters in the SUSY sector is much smaller than that in the general SUSY SM. Requiring the radiative electroweak symmetry breaking, we can take $\mu, M_2, \tan \beta$ and the charged Higgs mass as independent parameters after using the GUT relations among SU(3), SU(2) and U(1) gaugino masses. Then, all other Higgses’ and squarks’ masses and mixing parameters can be calculated with the help of the renormalization group equations. The detail of our calculation is described in Ref. [18].

In Fig. 1 the $b \to s \gamma$ branching ratio is shown for $m_t$ (top mass) = 175 GeV and $\tan \beta = 5$. Each point of this figure corresponds to a particular choice of free parameters. In the calculation we have taken account of various phenomenological constraints [32]: (i) the mass of any charged SUSY particle is larger than 45 GeV, (ii) the sneutrino mass is larger than 41 GeV, (iii) the gluino mass is larger than 100 GeV, (iv) neutralino search results at LEP [33], which require $\Gamma(Z \to \chi \chi) < 22$ MeV, $\Gamma(Z \to \chi' \chi'), \Gamma(Z \to \chi' \chi') < 5 \times 10^{-5}$ GeV, where $\chi$ is the lightest neutralino and $\chi'$ is any neutralino other than the lightest one, (v) the lightest SUSY particle (LSP) is neutral, (vi) the condition for not having a charge or color symmetry breaking vacuum [34]. We have neglected the neutralino loop contribution to the amplitude which is known to be very small. For comparison we also present the branching ratio which is calculated with only the SM and charged Higgs contributions retained. We can see that the predictions of the branching ratio are divided by the line of the THDM. In fact points above the line corresponds to the case $\mu < 0$ and below it to the case $\mu > 0$, respectively. Therefore, whether the SUSY particle effects enhance
Figure 1: $b \rightarrow s\gamma$ branching ratio for $m_t = 175$ GeV and $\tan \beta = 5$. Each dot corresponds to a sample point which satisfies radiative breaking and phenomenological constraints. Solid line represents the branching ratio calculated with the SM and charged Higgs contributions only (Model II THDM). Dot-dashed line represents the SM value.

or suppress the branching ratio depends on the sign of the $\mu$ parameter, which was pointed out previously\cite{7,12,15}. In Figs. 2 and 3, excluded region in the charged Higgs mass and $\tan \beta$ space from the $b \rightarrow s\gamma$ process is shown separately for $\mu < 0$ and $\mu > 0$. In accordance with the above discussion, the lower bound of the charged Higgs mass becomes much larger than that in the Model II THDM for $\mu < 0$, but no strong bound is obtained for $\mu > 0$ due to cancellation between the SUSY and other contributions. In determining the excluded region in the parameter space, we have calculated the $b \rightarrow s\gamma$ branching ratio varying free parameters ($\mu, M_2$) for each fixed set of the charged Higgs mass and $\tan \beta$. Since the main theoretical ambiguity comes from the choice of the renormalization scale ($Q$) at the bottom scale in evaluating the QCD correction \cite{30}, we have calculated the branching ratio by varying the renormalization scale from $Q = m_b/2$ to $Q = 2m_b$ where the bottom mass $m_b$ is taken to be 4.25 GeV. To be conservative, we also include additional 10 % theoretical uncertainties. Then, if the calculated branching ratio cannot be within the experimental value ($1 \times 10^{-4} < Br < 4 \times 10^{-4}$) for any choice of ($\mu, M_2$) even if the theoretical uncertainties are taken into account, we regard the point in the charged Higgs mass and $\tan \beta$ space excluded. In Fig. 4, two cases, $\mu < 0$ and $\mu > 0$ are combined and the excluded region is shown independently of the sign of $\mu$. For $3 \lesssim \tan \beta \lesssim 5$, the charged Higgs mass smaller than 180 GeV is excluded by this process. Due to the phenomenological constraints and the condition for radiative electroweak symmetry breaking, this region was previously allowed only for $\mu < 0$. 


Figure 2: Excluded region in the $\tan \beta$ and $m_{H^{\pm}}$ space for $\mu < 0$. Each line represents the lower bound for the charged Higgs mass: solid line: all constraints included; dashed line: without $b \rightarrow s\gamma$ constraint; dot-dashed line: Model II THDM with $b \rightarrow s\gamma$ constraint.

Figure 3: The same as Fig.2 for $\mu > 0$
Figure 4: Excluded region in the tan $\beta$ and $m_{H^\pm}$ space irrespective of the sign of $\mu$. The meaning of the lines are the same as those in Fig. 2.

It is, however, completely excluded by the new measurement of the $b \rightarrow s\gamma$ process.

4. $x_d$, $\epsilon_K$ and CP asymmetries in B decays

In the SM, all the flavor mixing and CP violating processes are determined by the parameters of the CKM matrix. There are four physical parameters in this matrix. A convenient way of the parametrization was given by Wolfenstein as follows\[35\]:

$$V_{CKM} \simeq \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & \lambda^3 A (\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & \lambda^2 A \\
\lambda^3 A (1 - \rho - i\eta) & -\lambda^2 A & 1
\end{pmatrix},$$

(5)

where we have ignored higher order terms in $\lambda$ in each element. Among four parameters the Cabbibo mixing parameter $\lambda$ and the $A$ parameter which is determined by $|V_{cb}|$ are well known experimentally. The $\rho$ and $\eta$ parameters are not yet precisely fixed. We can determine the present allowed region on the ($\rho$, $\eta$) space from three measured quantities, i.e., the CP violation parameter in K decays ($\epsilon_K$), the $B^0_d - \bar{B}^0_d$ mixing parameter ($x_d$) and $|V_{ub}|/|V_{cb}|$ from charmless $b$ decays.

When experiments on B decays are done at the asymmetric B factories we can directly measure three angle of the triangle formed by three points $0 + i0$, $1 + i0$, $\rho + i\eta$ in the complex plane. This is called the unitarily triangle. The time dependent asymmetry of the $B^0_d$ ($\bar{B}^0_d$) decay to a CP eigenstate ($f$) determines a quantity $\xi = Im \left( \frac{a}{p} \right)_B \left( \frac{A}{N_f} \right)$, where $\left( \frac{a}{p} \right)_B$ corresponds to the complex phase of the $B^0_d - \bar{B}^0_d$ box.
diagram and $A_f(A_f)$ is the amplitude of $B^0 \to f(\bar{B}^0 \to f)$\cite{30}. In the SM the $B^0 \to \psi K_s$ mode gives the angle $\phi_1$ (= angle at the point $1+i0$) which is in fact directly related to the phase of the $B^0_d - \bar{B}^0_d$ box diagram. $\phi_2$ (= angle at the point $\rho+i\eta$) is obtained from $B^0 \to \pi\pi$ or $\pi\rho$ process. The measurement of the angle $\phi_3$ (= angle at the point $0+i0$) can be done with direct CP violation in $B \to DK$ processes\cite{31}. Combining these measurements we will be able to determine the $\rho$ and $\eta$ parameters precisely. If the SM prediction is correct the parameter determined by these angle measurements should fall in the range obtained by the analysis of $\epsilon_K$, $x_d$ and $|V_{ub}|/|V_{cb}|$. Any inconsistency among these observables gives us a hint on physics beyond the SM.

In the minimal supergravity model the phase of the $B^0_d - \bar{B}^0_d$ box diagram is the same as that of the SM box diagram in a very good approximation, as we discussed in section 2. On the other hand the magnitude of the mixing can be different from the SM due to contributions from the charged Higgs and SUSY particles. The same is true for $\epsilon_K$ which is determined from the $K^0 - \bar{K}^0$ box diagram. Therefore, combining these observables with angle informations we may be able to get useful information on existence of SUSY particles.

We present calculation of $x_d$ and $\epsilon_K$ in the minimal supergravity model\cite{20}. In addition to the SM box diagram, we have included diagrams with the charged Higgs, chargino and up-type squarks, gluino and down-type squarks. One loop diagrams with neutralino are expected to be very small, therefore neglected here. In the calculation of these quantities we have taken into account the phenomenological constraints and the condition for the radiative electroweak symmetry breaking as described in the previous section. We have also included the constraint on the SUSY parameter space from the $b \to s\gamma$ process discussed in section 3. Fig. 5 shows a plot of $x_d = \frac{\Delta M_{B_d}}{\Gamma_{B_d}}$ in the SUSY model normalized by $x_d$ in the SM. This ratio does not contain the theoretical ambiguity of the hadron matrix element, i.e., $f^2_B B_B$. Here, we have taken $m_t = 175$ GeV, $\tan\beta = 2.5$ and $\rho = 0.18, \eta = 0.31$. In the supergravity model this ratio is almost independent of the values of $\rho$ and $\eta$ since the diagram containing squarks has almost the same $\rho$ and $\eta$ dependence as the SM box diagram. Here we have also shown the line corresponding to the case in which only the SM and the charged Higgs contributions are retained. We can see that the SUSY contributions always enhance the value of $x_d$. This is in contrast to the $b \to s\gamma$ case where cancellation between SUSY and other contributions is possible. (This is true even if we have not included the $b \to s\gamma$ constraint.) The SUSY and the charged Higgs contribution typically enhance $x_d$ by $10 \sim 20\%$. The enhancement is larger for smaller value of the charged Higgs mass. We also calculated this ratio for different values of $\tan\beta$. The result show that $x_d$ is larger for smaller $\tan\beta$. A similar plot is shown for $\epsilon_K$ in Fig. 6. The size of the SUSY and charged Higgs contributions is quite similar to that of $x_d$.

Since the effect of new particles are less than 20\%, $x_d$ and $\epsilon_K$ do not strongly constrain the SUSY parameter space from the present measurements. This is because large hadronic uncertainties exist in the calculation of $\epsilon_K$ and $x_d$, i.e. $B_K$, and $f^2_B B_B$, and also still two free parameters $\rho$ and $\eta$ remain in the prediction of the size of $\epsilon_K$ and $x_d$. The situation will be changed if independent information on
Figure 5: Ratio of $x_d$ in the supergravity model and that of the SM for $m_t = 175$ GeV and $\tan \beta = 2.5$. Each dot correspond to a sample point which satisfies radiative breaking and phenomenological constraints including the $b \to s \gamma$ constraint. Solid line represents the same ratio calculated with the SM and charged Higgs contributions only (Model II THDM).

Figure 6: The same figure as Fig.5 for the ratio of $\epsilon_K$ in the minimal supergravity model and that of SM. The solid line corresponds to Model II THDM.
the $\rho$ and $\eta$ parameters is obtained at the B factories. With expected improvement on determination of $B_K, f_B$ and $B_B$ from the lattice gauge theory in the next few years, the $10 \sim 20 \%$ effects on $x_d$ and $\epsilon_K$ can be large enough to detect new physics contributions like SUSY particles’ ones.

5. Conclusions

We have seen that SUSY particles and charged Higgs can contribute to various FCNC and CP violation processes like $b \rightarrow s\gamma$, $B^0 - \bar{B}^0$ mixing and $\epsilon_K$. They are induced not only by the usual quark flavor mixing but also by the squark’s counterpart. In the minimal supergravity model this squark’s flavor mixing is specified by a few free parameters so that the model has predictive power. We have seen that the prediction of the $b \rightarrow s\gamma$ branching ratio depends on the sign of the $\mu$ parameter. Then, the sensitivity to the charged Higgs mass is quite different for $\mu > 0$ and $\mu < 0$. We also calculated $x_d$ and $\epsilon_K$ in this model and have shown that these quantities are always enhanced compared to the SM prediction. The effects can be as large as $20 \%$ after taking account of the $b \rightarrow s\gamma$ constraint. These effects are large enough to give impacts on the new physics search at the B factories by measuring sides and angles of the unitarily triangle.

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