

## Neutrino oscillations, supersymmetric grand unification, and $B$ decay

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The effects of supersymmetric particles on flavor changing neutral current and lepton flavor violating processes are studied in supersymmetric SU(5) grand unified theory with right-handed neutrino supermultiplets. Using input parameters motivated by neutrino oscillation, it is shown that the time-dependent  $CP$  asymmetry of radiative  $B$  decay can be as large as 25% when the  $\tau \rightarrow \mu \gamma$  branching ratio becomes close to the present experimental upper bound. We also show that the  $B_s - \bar{B}_s$  mixing can be significantly different from the presently allowed range in the standard model.

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Although the standard model (SM) of elementary particle theory describes current experimental results very well, particles and interactions outside of the SM may appear beyond the energy scale available at current collider experiments. One of these indications is already given by the atmospheric and solar neutrino anomalies which have been interpreted as evidence of neutrino oscillation [1,2]. A natural way to introduce small neutrino masses for the neutrino oscillation is the seesaw mechanism [3] where the right-handed neutrino is introduced with a very heavy mass. This scenario suggests the existence of a new source of flavor mixing in the lepton sector at a much higher energy scale than the electroweak scale.

In this paper we consider flavor changing neutral current (FCNC) processes and lepton flavor violation (LFV) of charged lepton decays in the model of a SU(5) supersymmetric (SUSY) grand unified theory (GUT) which incorporates the seesaw mechanism for the neutrino mass generation. In the SUSY theory, the superpartners of quarks and leptons, namely squarks and sleptons, respectively, have new flavor mixings in their mass matrices. In the model based on the minimal supergravity these mass matrices are assumed to be flavor-blind at the Planck scale. However, renormalization effects due to Yukawa coupling constants can induce flavor mixing in the squark and slepton mass matrices. In the present model sources of the flavor mixing are Yukawa coupling constant matrices for quarks and leptons, as well as that for the right-handed neutrinos. Because the quark and lepton sectors are related by GUT interactions, the flavor mixing relevant to the Cabibbo-Kobayashi-Maskawa (CKM) matrix can generate LFV, such as  $\mu \rightarrow e \gamma$  and  $\tau \rightarrow \mu \gamma$  processes [4], in addition to FCNC in hadronic observables [5]. In the SUSY model with right-handed neutrinos, it is possible that the branching ratios of the LFV processes become large enough to be measured in near-future experiments [6]. When we consider the right-handed neutrinos in the context of

GUT, the flavor mixing related to the neutrino oscillation can be a source of the flavor mixing in the squark sector. We show that due to the large mixing of the second and third generations suggested by the atmospheric neutrino anomaly,  $B_s - \bar{B}_s$  mixing, the time-dependent  $CP$  asymmetry of the  $B \rightarrow M_s \gamma$  process, where  $M_s$  is a  $CP$  eigenstate including the strange quark, have a large deviation from the SM prediction.

The Yukawa coupling part and the Majorana mass term of the superpotential for the SU(5) SUSY GUT with right-handed neutrino supermultiplets is given by

$$W = \frac{1}{8} f_U^{ij} \Psi_i \Psi_j H_5 + f_D^{ij} \Psi_i \Phi_j H_{\bar{5}} + f_N^{ij} N_i \Phi_j H_5 + \frac{1}{2} M_\nu^{ij} N_i N_j, \quad (1)$$

where  $\Psi_i$ ,  $\Phi_i$ , and  $N_i$  are  $\mathbf{10}$ ,  $\bar{\mathbf{5}}$ , and  $\mathbf{1}$  representations of SU(5) gauge group.  $i, j = 1, 2, 3$  are the generation indices.  $H_5$  and  $H_{\bar{5}}$  are Higgs superfields with  $\mathbf{5}$  and  $\bar{\mathbf{5}}$  representations. In terms of SU(3)  $\times$  SU(2)<sub>L</sub>  $\times$  U(1)<sub>Y</sub>,  $\Psi_i$  contains  $Q_i(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ ,  $U_i(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$ , and  $E_i(\mathbf{1}, \mathbf{1}, 1)$  superfields. Here the representations for SU(3) and SU(2) groups and the U(1)<sub>Y</sub> charge are indicated in the parentheses.  $\Phi_i$  includes  $D_i(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$  and  $L_i(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ , and  $N_i$  is a singlet of SU(3)  $\times$  SU(2)<sub>L</sub>  $\times$  U(1)<sub>Y</sub>.  $M_\nu$  is the Majorana mass matrix. Below the GUT scale ( $M_G \approx 2 \times 10^{16}$  GeV) and the Majorana mass scale ( $\equiv M_R$ ) the superpotential for the minimal supersymmetric standard model (MSSM) fields is given by

$$W_{\text{MSSM}} = \tilde{f}_U^{ij} Q_i U_j H_2 + \tilde{f}_D^{ij} Q_i D_j H_1 + \tilde{f}_L^{ij} E_i L_j H_1 + \mu H_1 H_2 - \frac{1}{2} \kappa_\nu^{ij} (L_i H_2)(L_j H_2), \quad (2)$$

where  $\kappa_\nu$  is obtained by integrating out the heavy right-handed neutrino fields. At the right-handed neutrino mass scale  $\kappa_\nu$  is given as  $\kappa_\nu^{ij} = (f_N^T M_\nu^{-1} f_N)^{ij}$ . The Yukawa coupling constants  $\tilde{f}_U^{ij}$ ,  $\tilde{f}_D^{ij}$ , and  $\tilde{f}_L^{ij}$  are related to the coupling constants  $f_U^{ij}$  and  $f_D^{ij}$  at the GUT scale. The quark, charged

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lepton, and neutrino masses and mixings are determined from the superpotential, Eq. (2), at the low energy scale.

As discussed above, the renormalization effects due to the Yukawa coupling constants induce various FCNC and LFV effects from the mismatch between the quark or lepton and squark or slepton diagonalization matrices. In particular the large top Yukawa coupling constant is responsible for the renormalization of the  $\tilde{q}_L$  and  $\tilde{u}_R$  mass matrices. At the same time the  $\tilde{e}_R$  mass matrix receives sizable corrections between the Planck and the GUT scales and various LFV processes are induced. In a similar way, if the neutrino Yukawa coupling constant  $f_N^{ij}$  is large enough, the  $\tilde{L}_L$  mass matrix and the  $\tilde{d}_R$  mass matrix receive sizable flavor changing effects due to renormalization between the Planck and the  $M_R$  scales and the Planck and the GUT scales, respectively. These are sources of extra contributions to LFV processes and various FCNC processes, such as  $b \rightarrow s \gamma$ , the  $B^0 - \bar{B}^0$  mixing, and the  $K^0 - \bar{K}^0$  mixing.

It is particularly interesting to see that the chiral structure of the FCNC amplitudes due to the  $\tilde{d}_R$  mixing is different from that expected in the SM. For example, the flavor mixing in the  $\tilde{d}_R$  sector generates a sizable contribution to the  $b \rightarrow s \gamma_R$  amplitude through gluino- $\tilde{d}_R$  loop diagrams, whereas this amplitude is suppressed by a factor  $m_s/m_b$  over the dominant  $b \rightarrow s \gamma_L$  amplitude in the SM. When the amplitudes with both chiralities exist, the mixing-induced time-dependent  $CP$  asymmetry in the  $B \rightarrow M_s \gamma$  process can be induced. Using the Wilson coefficients  $c_7$  and  $c_7'$  in the effective Lagrangian for the  $b \rightarrow s \gamma$  decay  $\mathcal{L} = c_7 \bar{s} \sigma^{\mu\nu} b_R F_{\mu\nu} + c_7' \bar{s} \sigma^{\mu\nu} b_L F_{\mu\nu} + \text{H.c.}$ , the asymmetry is written as

$$\frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = \xi A_t \sin \Delta m_d t, \quad A_t = \frac{2 \text{Im}(e^{-i\theta_B} c_7 c_7')}{|c_7|^2 + |c_7'|^2},$$

where  $\Gamma(t)$  ( $\bar{\Gamma}(t)$ ) is the decay width of  $B^0(t) \rightarrow M_s \gamma$  ( $\bar{B}^0(t) \rightarrow M_s \gamma$ ) and  $M_s$  is some  $CP$  eigenstate [ $\xi = +1(-1)$  for a  $CP$  even (odd) state] such as  $K_1$  ( $\rightarrow K_S \rho^0$ ) or  $K^*$  ( $\rightarrow K_S \pi^0$ ) [7].  $\Delta m_d = 2|M_{12}(B_d)|$  and  $\theta_B = \arg M_{12}(B_d)$ , where  $M_{12}(B_d)$  is the  $B_d - \bar{B}_d$  mixing amplitude. Because the asymmetry can be only a few percent in the SM, a sizable asymmetry is a clear signal of new physics beyond the SM.

We calculated the following observables in the FCNC and LFV processes: the  $CP$  violation parameter in the  $K^0 - \bar{K}^0$  mixing  $\varepsilon_K$ ,  $B_d - \bar{B}_d$  and  $B_s - \bar{B}_s$  mass splittings  $\Delta m_d$  and  $\Delta m_s$ , respectively, and  $A_t$  and the branching ratios  $B(b \rightarrow s \gamma)$ ,  $B(\mu \rightarrow e \gamma)$ ,  $B(\tau \rightarrow \mu \gamma)$ , and  $B(\tau \rightarrow e \gamma)$ . We solved renormalization group equations (RGEs) for Yukawa coupling constants and the SUSY breaking parameters numerically keeping all flavor matrices. After demanding the condition of radiative electroweak symmetry breaking, the free parameters in the minimal supergravity model are the universal scalar mass  $m_0$ , the universal gaugino mass  $M_0$ , the scalar trilinear parameter  $A_0$ , the ratio of two vacuum expectation values  $\tan \beta$ , and the sign of the Higgsino mass

parameter  $\mu$ . In addition we need to specify neutrino parameters. The phenomenological inputs from neutrino oscillation are two mass-squared differences and the Maki-Nakagawa-Sakata (MNS) matrix. In order to relate these parameters to  $f_N$  and  $M_\nu$ , we work in the basis for  $N_i$ ,  $L_i$ , and  $E_i$ , where  $\hat{f}_L^{ij} = \hat{f}_L^{ij}$  and  $\hat{f}_N^{ij} = (\hat{f}_N V_L)^{ij}$  ( $\hat{f}_L$  and  $\hat{f}_N$  are diagonal matrix) at the matching scale  $M_R$ . In this basis  $\kappa_\nu = V_L^\dagger \hat{f}_N M_\nu^{-1} \hat{f}_N V_L = V_{\text{MNS}}^{0*} \hat{\kappa}_\nu V_{\text{MNS}}^{0\dagger}$  where  $V_{\text{MNS}}^0$  is the MNS matrix at  $M_R$  and  $\hat{\kappa}_\nu$  is a diagonal matrix. Note that although  $V_L = V_{\text{MNS}}^{0\dagger}$  when  $M_\nu$  is diagonal in this basis, two are independent in a general case. Once we specify three neutrino masses,  $V_{\text{MNS}}$ ,  $V_L$ , and  $\hat{f}_N$ , we can determine the  $M_\nu$  matrix. Then using the GUT relation for Yukawa coupling constants, we can calculate all squark and slepton mass matrices through RGEs. Note that  $V_L$  essentially determines the flavor mixing in the  $\tilde{d}_R$  and  $\tilde{L}_L$  sectors in this basis.

As typical examples of the neutrino parameters, we consider the following parameter sets, corresponding to (i) the Mikheyev-Smirnov-Wolfenstein (MSW) small mixing angle and (ii) the MSW large mixing angle solutions for the solar neutrino problem [2].

(i) small mixing:

$$m_\nu = (2.236 \times 10^{-3}, 3.16 \times 10^{-3}, 5.92 \times 10^{-2}) \text{ eV},$$

$$V_{\text{MNS}} = \begin{pmatrix} 0.999 & 0.0371 & 0 \\ -0.0262 & 0.707 & 0.707 \\ 0.0262 & -0.707 & 0.707 \end{pmatrix},$$

(ii) large mixing:

$$m_\nu = (4.0 \times 10^{-3}, 5.831 \times 10^{-3}, 5.945 \times 10^{-2}) \text{ eV},$$

$$V_{\text{MNS}} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix}.$$

Notice that the atmospheric neutrino as well as the solar neutrino anomalies can be explained by the neutrino oscillations with above parameter sets. In each example we also take  $M_\nu$  to be proportional to a unit matrix with a diagonal element of  $M_R = 4 \times 10^{14}$  GeV. In such a case, from the above input parameters we can determine  $V_L$  and  $\hat{f}_N$  as  $V_L = V_{\text{MNS}}^{0\dagger}$  and  $\hat{f}_N^{ii} = \sqrt{M_R \hat{\kappa}_\nu^{ii}}$ . We fix  $m_t^{\text{pole}} = 175$  GeV,  $m_b^{\text{pole}} = 4.8$  GeV, and the CKM parameters as  $V_{cb} = 0.04$ ,  $|V_{ub}/V_{cb}| = 0.08$ , and take several values of the phase parameter in the CKM matrix  $\delta_{13}$  [8]. We take  $\tan \beta = 5$  and vary other SUSY parameters  $m_0$ ,  $M_0$ ,  $A_0$ , and the sign of  $\mu$ . Various phenomenological constraints from SUSY particle searches are included (for detail see [9]). We also impose  $2 \times 10^{-4} < B(b \rightarrow s \gamma) < 4.5 \times 10^{-4}$  [11] in the following analysis.

Let us first discuss  $B(\mu \rightarrow e \gamma)$  and  $\varepsilon_K$ , which turn out to be strong constraints on the parameter space in this model. Figure 1 shows the correlation between  $B(\mu \rightarrow e \gamma)$  and  $B(\tau \rightarrow \mu \gamma)$  for the neutrino parameter set (i) and (ii) for

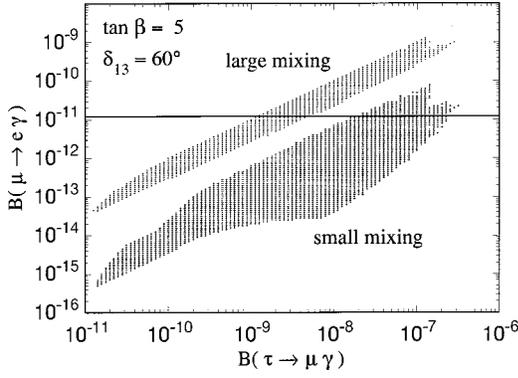


FIG. 1. The correlation between  $B(\mu \rightarrow e \gamma)$  and  $B(\tau \rightarrow \mu \gamma)$  for small and large mixing angle cases. See text for the input parameters.

$\delta_{13} = 60^\circ$ . We can see that  $B(\mu \rightarrow e \gamma)$  becomes a very strong constraint for case (ii), which is a reflection of the large 1–2 mixing in the  $V_{\text{MNS}}$  matrix. By requiring  $B(\mu \rightarrow e \gamma) < 1.2 \times 10^{-11}$  [12],  $B(\tau \rightarrow \mu \gamma)$  becomes less than  $10^{-8}$  for case (ii), whereas it can be close to the present experimental bound ( $1.1 \times 10^{-6}$  [13]) for case (i). We also calculated  $B(\tau \rightarrow e \gamma)$ , which turns out to be smaller than  $3 \times 10^{-12}$  in both cases. The constraint from  $\varepsilon_K$  depends on the parameter  $\delta_{13}$ . After imposing the  $B(\mu \rightarrow e \gamma)$  constraint,  $\varepsilon_K$  can be enhanced by 50% for case (i) and by a factor of 2 for case (ii). This means that compared to favorable values in the SM ( $50^\circ < \delta_{13} < 90^\circ$ ), a smaller value of  $\delta_{13}$  is allowed due to the extra contributions.

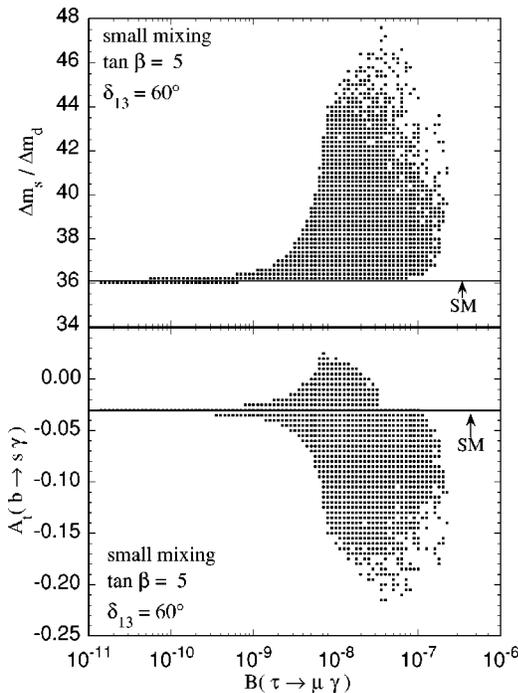


FIG. 2. The ratio of  $B_s - \bar{B}_s$  and  $B_d - \bar{B}_d$  mass splittings  $\Delta m_s / \Delta m_d$  and the magnitude factor  $A_t$  of the time-dependent  $CP$  asymmetry in the  $b \rightarrow s \gamma$  process as a function of  $B(\tau \rightarrow \mu \gamma)$  for the small mixing case (i).

The upper part of Fig. 2 shows a correlation between  $\Delta m_s / \Delta m_d$  and  $B(\tau \rightarrow \mu \gamma)$  for case (i) and  $\delta_{13} = 60^\circ$ . Here we imposed the constraints from  $B(\mu \rightarrow e \gamma)$  and  $\varepsilon_K$ . We also imposed the constraint from  $\Delta m_d$  itself, though the deviation of this quantity from the SM value is within 5%. For the theoretical uncertainties we allow a  $\pm 15\%$  difference for  $\varepsilon_K$  and  $\pm 40\%$  for  $\Delta m_d$ . For  $\Delta m_s / \Delta m_d$  we fix the hadronic parameters as  $f_{B_s} / f_{B_d} = 1.17$  and  $B_{B_s} / B_{B_d} = 1$ . We can see that  $\Delta m_s / \Delta m_d$  can be enhanced up to 30% compared to the SM prediction. This feature is quite different from the minimal supergravity model without the GUT and right-handed neutrino interactions [9] where  $\Delta m_s / \Delta m_d$  is almost the same as the SM value.  $A_t$  for the same parameter set is shown as a function of  $B(\tau \rightarrow \mu \gamma)$  in the lower part of Fig. 2. We can see that  $|A_t|$  can be close to 25% when  $B(\tau \rightarrow \mu \gamma)$  is larger than the  $10^{-8}$  level. The large asymmetry arises because the renormalization effect due to  $f_N$  induces sizable contributions to  $c_7'$  through gluino- $\tilde{d}_R$  loop diagrams. The corresponding figure to Fig. 2 for case (ii) shows that  $B(\tau \rightarrow \mu \gamma)$  is cut off below  $10^{-8}$ , the maximal deviation of  $\Delta m_s / \Delta m_d$  from SM is within 6%, and  $|A_t|$  becomes at most 6%.

In Fig. 3 we show  $\Delta m_s / \Delta m_d$  for several values of  $\delta_{13}$  for cases (i) and (ii). In these figures we impose the  $B(\mu \rightarrow e \gamma)$  constraint. Thin vertical lines correspond to the case without the experimental constraints from  $\varepsilon_K$ ,  $\Delta m_d$ , and the lower bound for  $\Delta m_s / \Delta m_d$  [10], and the thick lines are the allowed range with these constraints. The allowed range of the SM is also shown in these figures. Because the new contributions to the  $B_d - \bar{B}_d$  amplitude are small, the time-dependent  $CP$  asymmetry of  $B \rightarrow J/\psi K_S$  in this model is essentially the same as the SM value. Therefore we can obtain information on  $\delta_{13}$  once this asymmetry is measured experimentally. For example, the asymmetry of the  $B \rightarrow J/\psi K_S$  mode is 0.4 for  $\delta_{13} = 25^\circ$  and 0.65 for  $\delta_{13} = 75^\circ$ . This figure means the possible deviation from the SM may be seen in both cases once the  $CP$  asymmetry of the  $B \rightarrow J/\psi K_S$  mode and  $\Delta m_s / \Delta m_d$  are measured.

In our example we took  $M_R$ , which corresponds to the upper bound of  $f_N$  because a larger  $M_R$  would lead to the blow-up of  $f_N$  below the Planck scale. If we take a lower value of  $M_R$  the flavor changing amplitudes scale as  $M_R$ .

Finally we would like to comment on some generalizations of our result. First for a large  $\tan \beta$  case, the constraint from  $B(\mu \rightarrow e \gamma)$  becomes stronger. As a result we cannot see any deviation from the SM for the large mixing case in the figures corresponding to Figs. 2 and 3 for  $\tan \beta = 30$ , whereas the result is similar for the small mixing case. Second we considered the vacuum oscillation case. We see that the pattern of the deviation from the SM is similar to the small mixing case because the effect of the flavor mixing in 1–2 generations turns out to be suppressed by the degeneracy of the two light neutrino masses.

In this paper we took the superpotential (1). However, it is known that this superpotential does not lead to the realistic fermion mass relation, especially for the first and the second generations. In order to see how the above results change if we consider a model with realistic mass relation, we take

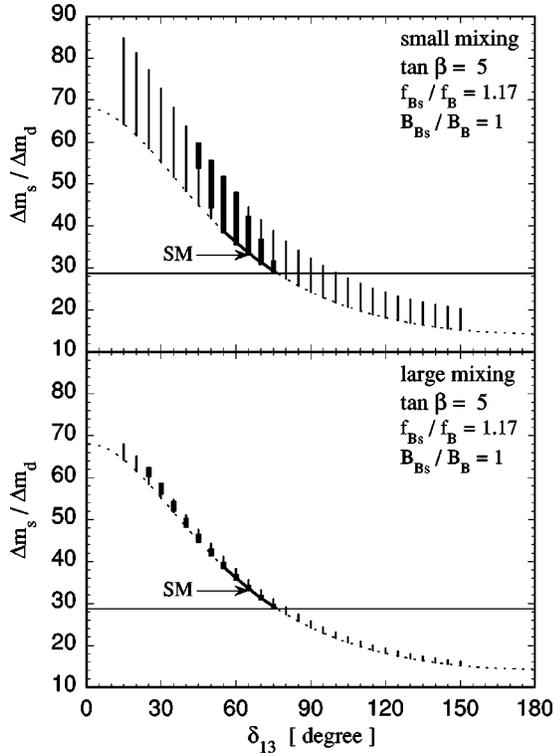


FIG. 3. Possible range of  $\Delta m_s/\Delta m_d$  as a function of  $\delta_{13}$  for the small and large mixing cases. Each thick vertical line shows the allowed range with the experimental constraints (see text). Thin vertical lines correspond to the case without the constraints from  $\varepsilon_K$ ,  $\Delta m_d$ , and  $\Delta m_s/\Delta m_d$ . Horizontal line shows the experimental lower bound of  $\Delta m_s/\Delta m_d$ . The dotted line corresponds to the SM value and the solid section shows the allowed range in the SM.

into account dimension-five operators in the superpotential. The simplest way to provide the realistic mass relation for the down-type quarks and charged leptons is to introduce the following dimension-five term:

$$\delta W = \frac{\kappa_D^{ij}}{M_P} (\Sigma \Psi_i) \Phi_j H_{\bar{5}}, \quad (3)$$

where  $M_P$  is the Planck mass and  $\kappa_D$  is an  $O(1)$  coupling matrix.  $\Sigma$  is a Higgs superfield with **24** representation whose VEV breaks the  $SU(5)$  symmetry down to  $SU(3) \times SU(2)_L$

$\times U(1)_Y$ . Below the GUT scale  $\delta W$  with  $\Sigma$  substituted by its VEV gives contributions of  $O(M_G/M_P)$  to the Yukawa coupling matrices for the down-type quarks and the charged leptons in a different manner so that the correct mass relation can be reproduced. Moreover, new degrees of freedom arise in the choice of the bases when the MSSM multiplets  $D_i$  and  $L_i$  are embedded in the  $SU(5)$  multiplet  $\Phi_i$ . We define a mixing matrix  $V_D$  as  $\Phi_i = \{(V_D D)_i, L_i\}$ , where the bases of  $D_i$  and  $L_i$  are taken as mass bases of fermions. Notice that in the absence of  $\delta W$  naive GUT relation among  $\tilde{f}_D$  and  $\tilde{f}_L$  requires  $V_D = 1$  (up to small corrections due to the running between the weak and the GUT scales). With a nonvanishing  $\delta W$ , however, a new mixing angle between the first and second generations arises in  $V_D$ . If  $\kappa_D$  is adjusted so that  $V_D = 1$ , the result given above does not change much. In a case with  $O(1)$  mixing in  $V_D$  for the first and second generations, the SUSY contribution to  $\varepsilon_K$  is significantly enhanced. After imposing the experimental constraint of  $\varepsilon_K$ , we see that the possible values of  $\Delta m_s/\Delta m_d$  and the time-dependent  $CP$  asymmetry of  $B \rightarrow J/\psi K_S$  lie along the dotted line of Fig. 3. Therefore the plot corresponding to Fig. 3 looks similar to the large mixing case with naive GUT relation (lower plot), except that the allowed range of  $\delta_{13}$  can be different, depending on the mixing parameter in  $V_D$ . Detailed discussions will be given elsewhere [14].

We have seen that there could be possible new physics signals such as  $B(\mu \rightarrow e \gamma)$ ,  $B(\tau \rightarrow \mu \gamma)$ ,  $B_s - \bar{B}_s$  mixing, the time-dependent  $CP$  asymmetry of  $b \rightarrow s \gamma$ , and the time-dependent  $CP$  asymmetry of  $B \rightarrow J/\psi K_S$  in the  $SU(5)$  SUSY-GUT model with right-handed neutrinos. Although the precise values of the predictions depend on the detail of the model in question, these signals may be expected as long as some of the neutrino Yukawa coupling constants are large. Because these signals provide quite different signatures compared to the SM and the minimal supergravity model without GUT and right-handed neutrino interactions, future experiments in  $B$  physics and LFV can provide us important clues on the interactions at very high energy scale.

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