Neutrino Yukawa couplings and FCNC processes in $B$ decays in SUSY-GUT

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Abstract

Flavor changing neutral current and lepton flavor violating processes are studied in the SU(5) SUSY-GUT with right-handed neutrino supermultiplets. Using input parameters motivated by neutrino oscillation, it is shown that the time-dependent CP asymmetry of $b \to s \gamma$ can be as large as 20%. We also show that the $B_d - \bar{B}_d$ mixing can be significantly different from the standard model prediction.

Effects of the physics beyond the standard model (SM) may appear in the flavor physics in quarks and leptons. One of indications is already given by the atmospheric and the solar neutrino anomalies which are interpreted as evidences of neutrino oscillation [1]. A natural way to explain small neutrino masses is the see-saw mechanism with very heavy right-handed neutrinos. This scenario suggests the existence of new sources of flavor mixings in the lepton sector at much higher energy scale than the electroweak scale.

In this work [2] we consider flavor changing neutral current (FCNC) and lepton flavor violation (LFV) processes in the model of a SU(5) supersymmetric (SUSY) grand unified theory (GUT) which incorporates the see-saw
mechanism for the neutrino masses. In the SUSY model based on the minimal supergravity the mass matrices of squarks and sleptons are flavor-blind at the Planck scale $M_P$. However renormalization effects due to Yukawa coupling constants of quarks, leptons and neutrinos induce flavor mixing in the squark/slepton mass matrices. In the context of SUSY-GUT with right-handed neutrinos, the flavor mixing related to the neutrino oscillation can provide the mixing in the squark sector. We show that due to the large mixing of the second and third generations suggested by the atmospheric neutrino data, $B_s$–$\bar{B}_s$ mixing and the CP asymmetry of the $B \rightarrow M_s\gamma$ process, where $M_s$ is a CP eigenstate including the strange quark, have significant deviations from the SM predictions.

The relevant part of the superpotential for the SU(5) SUSY GUT with right-handed neutrino supermultiplets is given by

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

(1)

where $\Psi_i, \Phi_i$ and $N_i$ are $\mathbf{10}, \mathbf{5}$ and $\mathbf{1}$ representations of SU(5) gauge group. $i,j = 1, 2, 3$ are the generation indices. $H_{5,\bar{5}}$ are Higgs superfields with $\mathbf{5}$ and $\bar{\mathbf{5}}$ representations. $f_{U,D,N}$ are Yukawa coupling matrices and $M_{\nu}$ is the Majorana mass matrix. Below the GUT scale $M_G$ and the Majorana mass scale $M_R$ the superpotential is written as

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

(2)

where $\kappa_{\nu}$ is obtained by integrating out $N_i$ at $M_R$. The Yukawa coupling constants $\tilde{f}_U, \tilde{f}_D$ and $\tilde{f}_L$ are related to $f_U$ and $f_D$ at $M_G$. The masses and mixings of the quarks and leptons 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/LFV effects from the mismatch between the bases of quark/lepton and squark/slepton masses. In particular the top Yukawa coupling constant is responsible for the running of the $\tilde{q}_L$ and $\tilde{u}_R$ masses. At the same time the $\tilde{e}_R$ mass matrix receives sizable corrections between $M_P$ and $M_G$ scales and LFV processes are induced $[3]$. In a similar way, if $f_N^{ij}$ is large, the $\tilde{l}_L$ and $\tilde{d}_R$ mass matrices receive sizable flavor changing effects due to the running between $M_P$ and $M_{G,R}$ scales $[4]$. These are sources of extra contributions to various FCNC/LFV processes.
We calculate the following observables: the CP violation parameter in the $K^0$--$ar{K}^0$ mixing $\varepsilon_K$, $B_q$--$\bar{B}_q$ mass splitting $\Delta m_q$ ($q = d, s$), the branching ratios of $b \to s \gamma$, $\mu \to e \gamma$ and $\tau \to \mu \gamma$, and the amplitude of the time-dependent CP asymmetry in the $B \to M_s \gamma$ process [3], which is written as

$$A_t = \frac{2 \text{Im}(e^{-i\theta_B} c_7 c'_7)}{|c_7|^2 + |c'_7|^2},$$

where $c_7$ and $c'_7$ are the Wilson coefficients in the effective Lagrangian for the $b \to s \gamma$ decay $\mathcal{L} = (c_7 \bar{s} \sigma^{\mu \nu} b_R + c'_7 \bar{s} \sigma^{\mu \nu} b_L) F_{\mu \nu} + \text{H.c.}$ where $\theta_B = \arg M_{12}(B_d)$ where $M_{12}(B_d)$ is the $B_d$--$\bar{B}_d$ mixing amplitude.

We solved renormalization group equations (RGEs) for Yukawa coupling matrices and the SUSY breaking parameters keeping all the flavor mixings. We specify neutrino parameters as well as the quark/lepton masses and the Cabibbo-Kobayashi-Maskawa (CKM) matrix as follows. The inputs from the neutrino oscillation are two mass differences and the Maki-Nakagawa-Sakata (MNS) matrix. In order to relate these inputs to $f_N$ and $M_\nu$, we work in the basis where $\hat{f}_L$ is diagonal and $f_N = \hat{f}_N V_L$ ($\hat{f}_N$ is diagonal). In this basis $\kappa_\nu = V^T_L \hat{f}_N M_\nu^{-1} \hat{f}_N V_L$ at the matching scale $M_R$. Once we fix three neutrino masses, $V_{\text{MNS}}$, $\hat{f}_N$ and the unitary matrix $V_L$ we can obtain $M_\nu$.

Then using the GUT relation for Yukawa coupling constants, we calculate all squark/slepton mass matrices through RGEs. Note that $V_L$ essentially determines the flavor mixing in the $\tilde{d}_R$ and $\tilde{l}_L$.

We consider the following parameter sets, corresponding to the Mikheyev-Smirnov-Wolfenstein solutions for the solar neutrino problem. (i) small mixing angle solution: $\sin^2 2\theta_{12} = 5.5 \times 10^{-3}$, $m_\nu = (2.24, 3.16, 59.2) \times 10^{-3}$ eV, (ii) large mixing angle solution: $\sin^2 2\theta_{12} = 1$. $m_\nu = (4.0, 5.83, 59.5) \times 10^{-3}$ eV, In both cases we take $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0$ and $M_\nu$ to be proportional to a unit matrix with a diagonal element of $M_R = 4 \times 10^{14}$ GeV so that $V_L = V^T_{\text{MNS}}$ at $M_R$. Free parameters in the minimal supergravity model are the universal scalar mass $m_0$, the unified 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 $\mu$. We take $\tan \beta = 5$ and vary other SUSY parameters. We also impose various constraints from SUSY particles search, the measurement of $B(b \to s \gamma)$ [3] and the search of $\mu \to e \gamma$ [7].

Fig. 1 shows $A_t$ as a function of $B(\tau \to \mu \gamma)$ [3] and the search of $\mu \to e \gamma$ [7].
Figure 1: Time-dependent CP asymmetry in $b \to s\gamma$ decay as a function of the branching ratio of $\tau \to \mu\gamma$.

is larger than $10^{-8}$ level. The large asymmetry arises because the renormalization effect of $f_N$ induces sizable contribution to $c'_7$ through gluino–$\tilde{d}_R$ loop diagrams. Since this asymmetry is suppressed by a factor $m_s/m_b$ in the SM, a sizable asymmetry is a clear signal of new physics beyond the SM.

In Fig. 2 we show allowed regions in the space of $\Delta m_s/\Delta m_d$ and the time-dependent CP asymmetry of $B \to J/\psi K_S$ for the case (i) and (ii). Here $|V_{ub}|$ is varied within $0.08 < |V_{ub}/V_{cb}| < 0.1$ and $\delta_{13}$ is scanned for the whole range. For the case (i) we see that the deviation of $A_t(B \to J/\psi K_S)$ from the SM value is small while $\Delta m_s/\Delta m_d$ can differ from the SM value by 40%. This pattern of deviation is understood as follows. The new contributions to $\varepsilon_K$ and $M_{12}(B_d)$ are suppressed due to the small 1-2 and 1-3 mixings in the neutrino sector so that the allowed region of $\delta_{13}$ does not change much. The deviation in $\Delta m_s/\Delta m_d$ comes from the SUSY contribution to $M_{12}(B_s)$ induced by the large 2-3 mixing in the neutrino sector. On the other hand we see a correlation between the deviations in the case (ii). Due to the large 1-2 mixing, $\varepsilon_K$ can be enhanced even after imposing the $B(\mu \to e\gamma)$ constraint in this case. Consequently the allowed range of $\delta_{13}$ by the constraint from $\varepsilon_K$
Figure 2: Allowed regions in the space of $\Delta m_s/\Delta m_d$ and the CP asymmetry in $B \to J/\psi K_S$ decay.

changes. The region with large deviations in both $\Delta m_s/\Delta m_d$ and $A_t(B \to J/\psi K_S)$ corresponds to a small $\delta_{13}$ region where the constraint from $\epsilon_K$ is satisfied by a large SUSY contribution. This figure means the deviation from the SM may be seen in both cases once $\Delta m_s/\Delta m_d$ and $A_t(B \to J/\psi K_S)$ are measured precisely.

In conclusion, we studied the effects of the neutrino Yukawa coupling matrix on FCNC/LFV processes in the SU(5) SUSY-GUT with right-handed neutrino supermultiplets. It is shown that $A_t(B \to M_s \gamma)$ can be $\sim 20\%$ when the $B(\tau \to \mu \gamma)$ is about $10^{-7}$. We also show that the $B_s - \bar{B}_s$ mixing can be significantly different from the presently allowed range in the SM. Since 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 give us important clues on the interactions at very high energy scale.

References
[1] E. Kearns, talk given at ICHEP 2000, Osaka, August 2000.

[2] S. Baek, T. Goto, Y. Okada and K. Okumura, [hep-ph/0002141].

[3] R. Barbieri and L. J. Hall, Phys. Lett. B338, 212 (1994);
J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B391, 341 (1997);
R. Barbieri, L. Hall and A. Strumia, Nucl. Phys. B445, 219 (1995);
N. G. Deshpande, B. Dutta and S. Oh, Phys. Rev. Lett. 77, 4499 (1996);

[4] F. Borzumati and A. Masiero, Phys. Rev. Lett. 57, 961 (1986);
J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi and T. Yanagida, Phys. Lett. B357, 579 (1995);
J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D53, 2442 (1996);
J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B437, 351 (1998);
J. Hisano and D. Nomura, Phys. Rev. D59, 116005 (1999);
J. Ellis, M. E. Gomez, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C14, 319 (2000);

[5] D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. 79, 185 (1997);
C. Chua, X. He and W. Hou, Phys. Rev. D60, 014003 (1999).

[6] S. Ahmed et al., [CLEO Collaboration], CLEO CONF 99-10 (1999).

[7] M. L. Brooks et al. [MEGA Collaboration], Phys. Rev. Lett. 83, 1521 (1999).