PHYSICAL REVIEW D, VOLUME 58, 032004

Lepton flavor violation at linear collider experiments in supersymmetric grand unified theories

Masahide Hirouchi and Minoru Tanaka*

Department of Physics, Graduate School of Science, Osaka University, Toyonaka, Osaka 560, Japan

(Received 29 December 1997; published 6 July 1998)

Lepton flavor violation at linear collider experiments is discussed. We show that detectable lepton flavor violation could occur in scalar lepton pair production and decay in the supersymmetric SU(5) grand unified theory in spite of the stringent present experimental constraints by searches for rare processes. Possible cross sections of $\sim$40 fb for an e^+e^- collider and $\sim$280 fb for an e^-e^- collider are illustrated.

[S0556-2821(98)02815-X]

PACS number(s): 12.60.Jv, 14.80.Ly

I. INTRODUCTION

The search for lepton flavor violation (LFV) is one of the most important ways to explore physics beyond the standard model, because lepton flavors are conserved individually in the standard model. In the standard model with supersymmetry (SUSY), which is one of the most attractive extensions of the standard model, LFV is allowed. The soft SUSY breaking masses of the scalar leptons (sleptons) do not have to conserve the lepton flavors in general. However, the resulting LFV exceeds much the present experimental bounds such as the one from a $\mu \rightarrow e\gamma$ search if an arbitrary, but consistent with the naturalness argument, set of slepton soft masses is allowed. The universal soft mass scenario lead from supergravity [1] is often assumed to avoid this large LFV (and the same problem in the scalar quark sector). In this scenario, all the sleptons degenerate and we have no flavor mixing in the lepton and slepton sectors.

However, this is not the whole story when a grand unified theory (GUT) is considered at the same time [2]. In SUSY GUTs with universal soft breaking at the Planck scale, the large top quark Yukawa coupling affects the third generation slepton mass through renomalization group evolution from the Planck scale to GUT scale, since quark and lepton supermultiplets are unified into larger GUT multiplets. As a result, the sleptons degenerate no longer and LFV is expected to take place.

Along this line, rates of $\mu \rightarrow e\gamma$ decay, $\mu \rightarrow 3e$ decay, $\tau \rightarrow \mu\gamma$ decay, and $\mu \rightarrow e$ conversion in nuclei have been estimated in the literature [3,4]. In the minimal SU(5) model, the $\mu \rightarrow e\gamma$ branching ratio has been found to be typically one or two orders below the present experimental upper bound (4.9×10^{-11} [5]). The other modes tend to give two or more orders smaller values than experimental bounds. In the SO(10) model, the $\mu \rightarrow e\gamma$ amplitude is enhanced by a factor m_τ/m_μ due to its chiral structure different from the SU(5) model, and thus the decay rate could be the same order as or even larger than the experimental bound [3].

In addition to these rare processes caused by virtual slepton exchange, it is possible to search for LFV in the real production of a slepton and its successive decay [6–9]. The most prominent qualitative difference between the virtual and the real processes can be seen in behaviors of their amplitudes as the sleptons are getting degenerate. The virtual process behaves as $\Delta m^2/\overline{m}^2$, while the real process behaves as $\Delta m^2/(\overline{m}\Gamma)$ [6], where Δm^2 is a slepton mass squared difference, $\overline{m}$ is the average mass of the sleptons, and Γ is the average slepton width. Because $\overline{m} \gg \Gamma$, we expect that there is a good chance to observe LFV even for relatively degenerate sleptons once their real production at collider experiments becomes possible. The advantage of real production is maximized if $\Delta m^2/\overline{m}^2 \ll 1 \ll \Delta m^2/(\overline{m}\Gamma)$ is realized. In the following, we show that this happens in the minimal SUSY SU(5) model.

Another important point needed in order to have a realistic LFV cross section of the real production and decay is the necessity of relatively large flavor mixing in the lepton-slepton sector. In the minimal SUSY SU(5) model, the leptons and down-type quarks have the same Yukawa couplings at the GUT scale. This means that LFV is essentially controlled by the Cabibbo-Kobayashi-Maskawa (CKM) matrix which describes the quark mixing. Since the CKM matrix is almost diagonal [10], LFV cross sections are suppressed by the small off-diagonal elements of the CKM matrix. It will be shown later that LFV cross sections at linear collider experiments are hopelessly small in the minimal SUSY SU(5) model.

However, the minimal SUSY SU(5) model is nothing more than a calculable example. In fact, it cannot describe the whole known fermion masses and mixing [11]. The above-mentioned equality of the down-type quark Yukawa couplings and the leptonic ones leads to an inconsistent mass relation for the first and second generations, although it gives the celebrated bottom quark to tau mass ratio. Once we extend the model to overcome this insufficiency, the leptonic Yukawa couplings do not have to be the same as the down-type quark Yukawa couplings. Thus, the leptonic mixing is independent of the CKM matrix in general.

In this paper, we show that LFV cross sections of charged slepton pair production and decay at linear collider experiments are sizable if the lepton mixing has some appropriate structures. In Sec. II, we describe our framework based on SUSY SU(5) GUT more explicitly. Our numerical results on present experimental constraints and LFV cross sections are presented in Sec. III. Section IV is devoted to concluding remarks.

*Email address: tanaka@phys.wani.osaka-u.ac.jp

II. FRAMEWORK

Apart from the Yukawa sector, our working model is the minimal SUSY SU(5) GUT with the universal soft SUSY breaking terms at the Planck scale, discussed in detail in Ref. [3] in the context of LFV. The quarks and leptons are unified into three pairs of SU(5) chiral supermultiplets, 10 (T_i) and $\overline{5}$ $(\overline{F_i})$, with their superpartners, where $i=1,2,3$ is a generation index. As for the Higgs sector, we assume the minimal one, i.e., 24 (Σ), 5 (H), and $\overline{5}$ $(\overline{H})$.

In the minimal model, the Yukawa superpotential is

$$W_0 = T_i f^T_{ij} T_j H + T_i f^F_{ij} \overline{F_j}\,\overline{H}, \tag{1}$$

where f^T is the Yukawa coupling matrix which gives up-type quark masses, and f^F is the one giving down-type quark and charged lepton masses. We can take f^T to be diagonal without loss of generality. Thus, the flavor mixing in the lepton sector as well as the quark sector is governed by f^F in the minimal model. As will be shown later, LFV cross sections of charged slepton pair production and decay are too small to be measured in this case.

However, as mentioned in Sec. I, the above minimal model is known to give an incorrect mass relation for the first and the second generations. To be realistic, it is natural to extend Eq. (1). As a result, we expect that the leptonic Yukawa matrix is different from the down-type one. This is realized, for instance, by introducing the following higher dimensional term that might be induced by gravity [12]:

$$W_1 = \frac{f'_{ij}}{M_{\mathrm{Planck}}} \overline{F}^{\alpha}_i \Sigma^{\beta}_{\alpha} T_{j,\beta\gamma} \overline{H}^{\gamma}, \tag{2}$$

where the Greek indices are SU(5) ones. Note that the effective Yukawa coupling $f'\langle\Sigma\rangle/M_{\mathrm{Planck}} \sim f' M_{\mathrm{GUT}}/M_{\mathrm{Planck}}$ could have the same order of magnitude as f^F due to the small masses of the bottom quark and tau, provided that $f' \sim O(1)$ and $\tan\beta = \langle H\rangle/\langle \overline{H}\rangle$ is not too large.

In the following, we do not discuss specific extensions such as Eq. (2). Instead, we simply regard the leptonic mixing as independent from the quark mixing.

The lepton mass matrix at the weak scale M_e is diagonalized as $\overline{e_L} M_e e_R = \overline{\ell}_L D_e \ell_R$ by unitary transformations $e_R = V_e \ell_R$ and $e_L = U_e \ell_L$, where $M_e = U_e D_e V_e^\dagger$, $D_e = \mathrm{diag}\ (m_e, m_\mu, m_\tau)$, $e_{R,L}$ denote the gauge eigenstates, $\ell_{R,L}$ are the mass eigenstates, and generation indices are suppressed. Making the same unitary transformations for corresponding sleptons, we obtain the following 6×6 charged slepton mass matrix:

$$(\tilde{e}_L^\dagger, \tilde{e}_R^\dagger) \begin{pmatrix} m_L^2 & m_{LR}^2 \\ m_{LR}^{2\,\dagger} & m_R^2 \end{pmatrix} \begin{pmatrix} \tilde{e}_L \\ \tilde{e}_R \end{pmatrix}, \tag{3}$$

$$m_L^2 = \overline{m_L^2}\mathbf{1}, \quad m_R^2 = \overline{m_R^2}\mathbf{1} - V_e^\dagger \boldsymbol{I} V_e,$$

$$m_{LR}^2 = -D_e\left(A_e \mathbf{1} - \frac{1}{3} V_e^\dagger \boldsymbol{I}' V_e + \mu\ \tan\beta \mathbf{1}\right),$$

$$\boldsymbol{I} = \mathrm{diag}\ (0,0,I), \boldsymbol{I}' = \mathrm{diag}\ (0,0,I'),$$

where $\mathbf{1}$ is the 3×3 unit matrix, $\overline{m^2_{L(R)}}$ denotes the degenerate left(right)-handed charged slepton mass squared coming from the soft and electroweak breakings, A_e is the universal soft breaking trilinear coupling for the slepton, I denotes the shift of the soft breaking mass of the third generation charged slepton coming from the renormalization group evolution from M_{Planck} to M_{GUT} due to the large top quark Yukawa coupling, and I' is the similar shift of the soft breaking trilinear coupling. The renomalization group equations necessary to evaluate these quantities can be found in Ref. [3].

Because of the degeneracy of the left-handed slepton soft masses, U_e does not appear in Eq. (3). Thus, LFV is controlled by a 3×3 unitary matrix V_e. It turns out that V_e contains only two parameters since, as seen in Eq. (3), the first and second generation right-handed slepton soft breaking parameters are the same. In addition, apparently no CP violating complex phase exists in V_e. In the following analysis, we take absolute values of (3,1) and (3,2) elements of V_e as the independent parameters in V_e. We denote them as $|V_{31}|$ and $|V_{32}|$.

III. NUMERICAL RESULTS ON LFV

By diagonalizing Eq. (3) numerically, we calculate rates of several LFV processes as functions of $|V_{31}|$ and $|V_{32}|$. Masses and couplings of SUSY particles at the weak scale are determined through the renomalization group equations by giving the universal scalar mass (m_0), the GUT gaugino mass (M_0), and the universal A parameter (A_0) at the Planck scale, in addition to the sign of the supersymmetric Higgsino mass (μ), $\tan\beta$, $|V_{31}|$, and $|V_{32}|$ at the weak scale. For illustrative purposes, we take $m_0 = 100$ GeV, $M_0 = 150$ GeV $A_0 = 0$, and $\mathrm{sgn}(\mu) = +1$. As for $\tan\beta$, results for $\tan\beta = 3$ and 10 are shown. The top quark mass is assumed to be 175 GeV. These input parameters are consistent with the present experiments [13], other than the LFV experiments discussed below, for all possible values of $|V_{31}|$ and $|V_{32}|$. The lightest SUSY particle (LSP) is the lightest neutralino, which is almost B-ino, with a mass of around 63 GeV depending on $\tan\beta$. The mass spectrum of the six charged sleptons is given as (150,163,163,182,182,183) GeV for $\tan\beta = 3$ and (149,164,164,183,183,190) GeV for $\tan\beta = 10$. The precise values of the charged slepton masses depend on V_e and the above values are obtained for $V_e = \mathbf{1}$. The lightest charged slepton, whose production and decay with LFV is discussed below, decays mostly into a LSP and a charged lepton. A typical decay width of the charged sleptons is ~ 0.5 GeV for the above parameters. Note that $\Delta m^2/\overline{m}^2 \ll 1 \ll \Delta m^2/(\overline{m}\Gamma)$ is realized as mentioned in Sec. I.

Before discussing cross sections at linear collider experiments, let us examine constraints on $|V_{31}|$ and $|V_{32}|$ from present LFV experiments. The constraint from

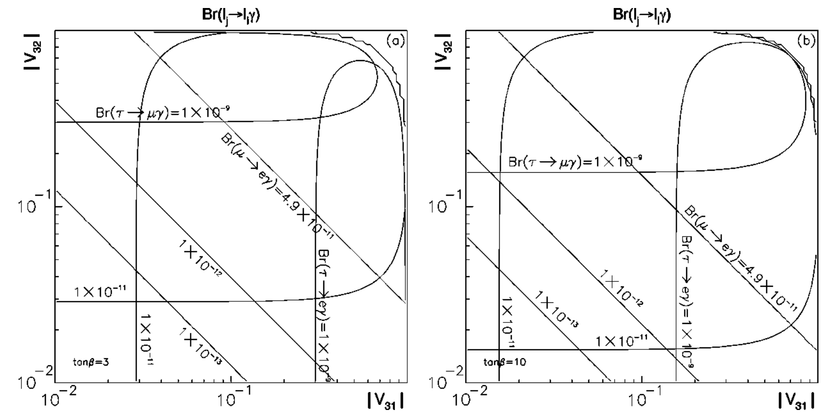

FIG. 1. Present experimental constraint on $|V_{31}|$ and $|V_{32}|$ from a $\mu\to e\gamma$ search: (a) for tan $\beta=3$ and (b) for tan $\beta=10$. B[$\tau\to\mu(e)\gamma$] is also shown.

B($\mu\to e\gamma$)$<4.9\times10^{-11}$ [5] is shown in Fig. 1. We also show lines for 1×10^{-12} and 1×10^{-13}. Figure 1(a) is the case of tan $\beta=3$ and Fig. 1(b) is the case of tan $\beta=10$. For larger tan β, the constraint is stronger because the $\mu\to e\gamma$ rate increases as tan β increases [3,4]. We can see from Fig. 1 that $\mu\to e\gamma$ mainly gives a constraint on $|V_{31}V_{32}|$. In Fig. 1, we also show branching ratios of $\tau\to\mu\gamma$ and $\tau\to e\gamma$. The present experimental upper bound for B($\tau\to\mu(e)\gamma$) is $3.0(2.7)\times10^{-6}$ [14], and no constraint on the $|V_{31}|$–$|V_{32}|$ plane is obtained. $\tau\to\mu(e)\gamma$ constrains $|V_{33}V_{32}|(|V_{33}V_{31}|)$ as is expected.

$\mu\to e$ conversion and $\mu\to 3e$ decay also give similar constraints on the $|V_{31}|$–$|V_{32}|$ plane as $\mu\to e\gamma$. Since they tend to be weaker than the $\mu\to e\gamma$ constraint [3,4], we do not discuss them for simplicity.

In Fig. 2, we show cross sections of LFV processes in pair production of the lightest charged sleptons at linear collider experiments in the case of tan $\beta=3$. Figure 2(a) shows the total cross section of $e^+e^-_R\to\tilde{l}^+_1\tilde{l}^-_1\to\tau\mu+2$ LSPs, where $\tilde{l}^\pm_1$ denotes the lightest charged slepton. We assume $\sqrt{s}=500$ GeV and 100% right-handed polarization of the electron beam. The $\mu\to e\gamma$ constraint is also shown for compari-

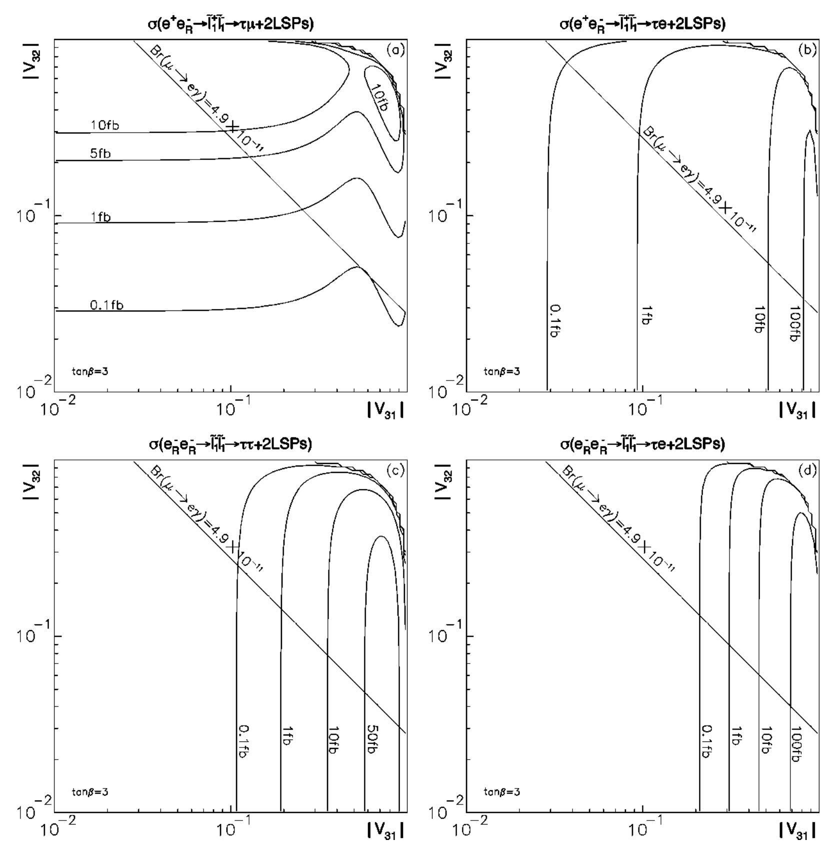

FIG. 2. LFV cross sections at $\sqrt{s}=500$ GeV for tan $\beta=3$. The $\mu\to e\gamma$ constraint is also shown for comparison.

son. We expect 40 fb as the maximal cross section in spite of the strong constraint because of the different dependence on V_e from $\mu \to e\gamma$. This process depends on V_e mainly through combinations of $|V_{33}V_{32}|$ and $|V_{33}V_{32}V_{31}^2|$ corresponding to the s- and t-channel diagrams, respectively. The allowed maximal LFV cross section is obtained in the case where $|V_{31}| \ll |V_{32}| \simeq |V_{33}|$. Note that the LFV cross section is $O(0.1)$ fb if V_e has a structure similar to the CKM matrix as in the minimal SU(5) model.

Figures 2(b)–2(d) show the total cross cross sections of $e^+e_R^- \to \tilde{\ell}_1^+\tilde{\ell}_1^- \to \tau e + 2$ LSPs, $e_R^-e_R^- \to \tilde{\ell}_1^-\tilde{\ell}_1^- \to \tau\tau + 2$ LSPs, and $e_R^-e_R^- \to \tilde{\ell}_1^-\tilde{\ell}_1^- \to \tau e + 2$ LSPs, respectively. The same $\sqrt{s}$ and beam polarization as in Fig. 2(a) are assumed. The maximal values of cross sections are about 150, 80, and 280 fb, respectively. These values are realized in the case where $|V_{32}| \ll |V_{31}| \sim |V_{33}|$. Other lepton flavor violating combinations in the final state charged lepton pair give less interesting cross sections for both $e^+e_R^-$ and $e_R^-e_R^-$ collisions.

Figure 3 shows the same quantities as Fig. 2, but for $\tan\beta = 10$. Comparing Fig. 3 with Fig. 2, we find that the LFV cross sections are smaller for larger $\tan\beta$. This means that these processes are complimentary to $\mu \to e\gamma$ which is enhanced for larger $\tan\beta$.

The reduction of the LFV cross sections for larger $\tan\beta$ is due to large left-right mixing of scalar tau leptons. To see this, it is enough to consider the following 3×3 submatrix of Eq. (3):

$$M^2 = \begin{pmatrix} (m_L^2)_{33} & (m_{LR}^2)_{32} & (m_{LR}^2)_{33} \\ * & (m_R^2)_{22} & (m_R^2)_{23} \\ * & * & (m_R^2)_{33} \end{pmatrix} \simeq \begin{pmatrix} \overline{m}_L^2 & 0 & -m_\tau\mu \tan\beta \\ * & \overline{m}_R^2 - IV_{32}^2 & -IV_{32}V_{33} \\ * & * & \overline{m}_R^2 - IV_{33}^2 \end{pmatrix}, \tag{4}$$

where we neglect terms other than the one proportional to $m_\tau \tan\beta$ in m_{LR}^2. Since we are considering a large $\tan\beta$ case, the left-right mixing angle of the scalar tau leptons is almost 45°. By making the 45° rotation in the 1–3 plane of M^2, we obtain a matrix closer to a diagonal form:

$$O_0^T M^2 O_0 = \begin{pmatrix} \dfrac{\overline{m}_L^2 + \overline{m}_R^2 - IV_{33}^2}{2} + m_\tau|\mu|\tan\beta & -\dfrac{\mu}{\sqrt{2}|\mu|}IV_{32}V_{33} & \dfrac{\mu}{2|\mu|}(\overline{m}_L^2 - \overline{m}_R^2 + IV_{33}^2) \\ * & \overline{m}_R^2 - IV_{32}^2 & IV_{32}V_{33}/\sqrt{2} \\ * & * & \dfrac{\overline{m}_L^2 + \overline{m}_R^2 - IV_{33}^2}{2} - m_\tau|\mu|\tan\beta \end{pmatrix}, \tag{5}$$

where O_0 is the 45° rotation matrix

$$O_0 = \begin{pmatrix} \dfrac{1}{\sqrt{2}} & 0 & \dfrac{\mu}{|\mu|\sqrt{2}} \\ 0 & 1 & 0 \\ -\dfrac{\mu}{|\mu|\sqrt{2}} & 0 & \dfrac{1}{\sqrt{2}} \end{pmatrix}. \tag{6}$$

It is legitimate to diagonalize Eq. (5) perturbatively in order to see the qualitative behavior of the slepton flavor mixing. As a result, we find that LFV related off-diagonal elements of the slepton mixing matrix are approximately proportional to

$$\sim \frac{I}{m_\tau|\mu|\tan\beta} \tag{7}$$

in the large $\tan\beta$ case. Thus, the LFV cross sections are suppressed as $\tan\beta$ becomes large.

IV. CONCLUDING REMARKS

Before concluding we discuss some background issues. Possible extensions of our calculation are also discussed here.

Our LFV signals are $\tau^\pm \ell^\mp +$ missing where ℓ denotes e or μ for the e^+e^- collision, and $\tau^-\ell^- +$ missing with $\ell = e$ or τ for the e^-e^- collision. The tau leptons are identified by their hadronic decays. The pure leptonic decay modes can also be useful in principle if impact parameter analysis is available. A CCD pixel vertex detector proposed for linear collider experiments has a typical resolution better than 10 μm [15], while $c\tau$ of the tau lepton is about 90 μm [10].

The most serious standard model background in the e^+e^- collision is the one coming from W boson pair production. The leptonic W pair decay $WW \to \tau\ell\nu\nu$ ($\ell = e, \mu$) is a background event. $WW \to \tau\tau\nu\nu$ followed by a pure leptonic decay of one of the τ's can also be a background although appropriate kinematical cuts and the above mentioned impact parameter analysis can reduce it significantly. These WW backgrounds are reduced by employing a right-handed electron beam as we did in the above calculation. Eventually, the WW background cross section is reduced to less than $O(1)$

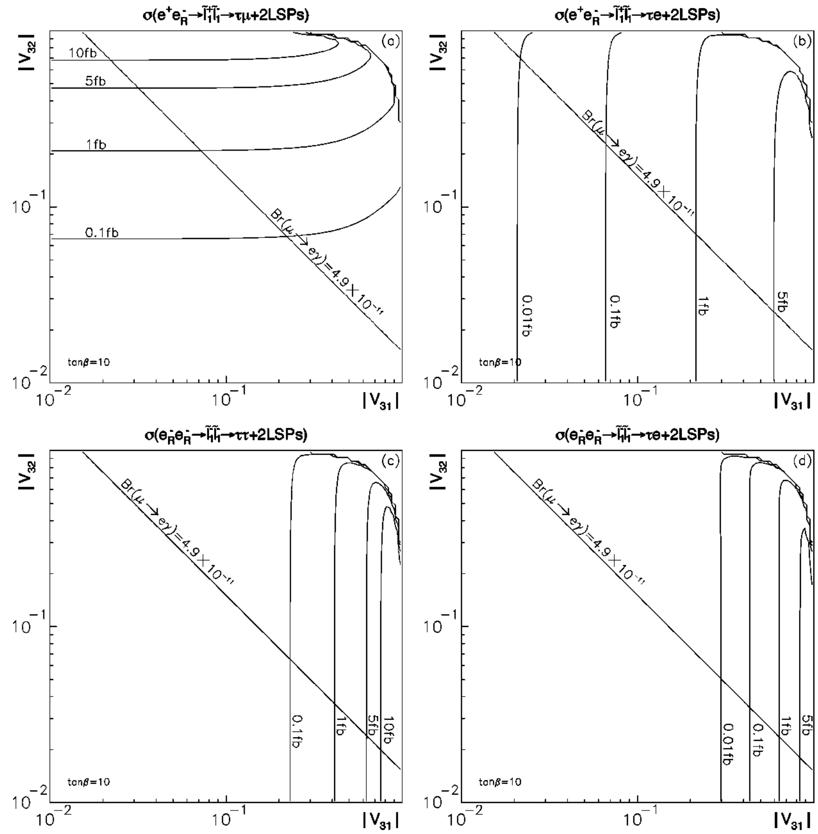

FIG. 3. The same as Fig. 2 except for tan $\beta=10$.

fb with a reasonable efficiency (30–50 %) for the signal [16,17]. $e\overline{\nu}W$ and $eeWW$ could also be backgrounds of $O(1)$ fb [16]. ZZ, Zh, and $ee\tau\tau$ could also be backgrounds. They can be reduced to $O(1)$ fb or less by appropriate selection cuts [16,17].

Assuming 3 fb background in total and 30% efficiency for the signal, the required signal cross section at the 5σ level is ~ 4 fb for the integrated luminosity of 50 fb^{-1} [6]. We see, e.g., from Fig. 2(a) that $|V_{32}| \sim O(0.1)$ can be detected.

As for the e^-e^- collision, our LFV signals are essentially free from backgrounds. In particular, the right-handed beams reduce the $e^-\nu W^-$ mode to a negligible level without any selection cuts [18].

Production of other superparticles could also be backgrounds. In particular, heavier slepton production makes LFV signals more complicated. To avoid this, we can choose such a $\sqrt{s}$ that only a pair of the lightest charged sleptons is created. Although the cross sections, especially the s-channel contribution in the e^+e^- collision, decrease near the threshold, we still have sizable cross sections for both the e^+e^- and the e^-e^- collisions. In the case of tan $\beta=3$, for instance, at $\sqrt{s}=m_{\tilde{l}_1}+m_{\tilde{l}_2}$, i.e. just at the threshold for the second lightest charged slepton, we expect 3(6) fb for the $\tau\mu(\tau e)$ mode in the $e^+e_R^-$ collision, and 75(250) fb for the $\tau\tau(\tau e)$ mode in the $e_R^-e_R^-$ collision.

Our observations in the present work can also be applied to other SUSY GUTs qualitatively. For instance, the LFV cross sections are expected to be sizable in the SO(10) model. In this model, the left-handed sleptons, as well as the right-handed ones, cause LFV since the left-handed lepton supermultiplet of the third generation is unified into the same GUT multiplet as the top quark. Then, as mentioned in Sec. I, the $\mu \to e\gamma$ rate is enhanced by a factor $\sim m_\tau/m_\mu$ because of the chirality-flip nature of this process, while $\tau \to \mu(e)\gamma$ is not enhanced. Although the details depend on the model, especially its Yukawa superpotential, we expect a stronger constraint from $\mu \to e\gamma$ and similar constraints from $\tau \to \mu(e)\gamma$ compared with the SU(5) model. As can be seen in Figs. 2 and 3, a stronger $\mu \to e\gamma$ constraint alone does not exclude sizable LFV cross sections.

We also expect sizable LFV cross sections from a muon collider experiment [19]. The s-channel amplitude in the $\mu^+\mu^-$ collision is the same as in the e^+e^- case, while the t-channel one has a different dependence on V_e. The lower initial state radiation of the muon collider would make the threshold operation mentioned above more effective.

In conclusion, we have shown that LFV phenomena in slepton pair production and decay could be detectable at linear collider experiments in the SUSY SU(5) GUT. Treating the lepton mixing matrix as a set of parameters independent of the CKM matrix, we have discussed the constraints on it from the present experiments and calculated LFV cross sections. In spite of the stringent constraint from $\mu \to e\gamma$, some of the LFV processes which have tau lepton(s) in the final state could have sizable cross sections in future linear collider experiments.

[1] For a review, see, e.g., H. P. Nilles, Phys. Rep. **110**, 1 (1984).
[2] L. J. Hall, V. A. Kostelecky, and S. Raby, Nucl. Phys. **B267**, 415 (1986).
[3] R. Barbieri and L. J. Hall, Phys. Lett. B **338**, 212 (1994); R. Barbieri, L. J. Hall, and A. Strumia, Nucl. Phys. **B445**, 219 (1995).
[4] J. Hisano *et al.*, Phys. Rev. D **53**, 2442 (1996); Phys. Lett. B **391**, 341 (1997); **397**, 357(E) (1997).
[5] R. D. Bolton *et al.*, Phys. Rev. D **38**, 2077 (1988).
[6] N. Arkani-Hamed *et al.*, Phys. Rev. Lett. **77**, 1937 (1996).
[7] N. Arkani-Hamed *et al.*, Nucl. Phys. **B505**, 3 (1997).
[8] N. V. Krasnikov, Mod. Phys. Lett. A **9**, 791 (1994); Phys. Lett. B **388**, 783 (1996).
[9] N. V. Krasnikov, JETP Lett. **65**, 148 (1997); S. I. Bityukov and N. V. Krasnikov, Report No. IFVE-97-67, hep-ph/9712358.
[10] Particle Data Group, R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).
[11] For a recent review on fermion masses and mixing in SUSY GUT, see, e.g., Z. Berezhiani in ‘‘Proceedings of ICTP Summer School in High-energy Physics and Cosmology, Trieste, Italy, 1995,’’ edited by E. Gava *et al.*, hep-ph/9602325.
[12] J. Ellis and M. K. Gaillard, Phys. Lett. **88B**, 315 (1979).
[13] P. Janot, talk given at *International Europhysics Conference on High Energy Physics*, 1997, Jerusalem, Israel (unpublished).
[14] CLEO Collaboration, K. W. Edwards *et al.*, Phys. Rev. D **55**, 3919 (1997).
[15] C. J. S. Damerell and D. J. Jackson, in *Proceedings of the Workshop on Physics and Experiments with Linear Colliders, Morioka-Appi*, Iwate, Japan, 1995, edited by A. Miyamoto *et al.* (unpublished).
[16] R. Becker and C. Vander Velde, in ‘‘Proceedings of the European Meeting of the Working Groups on Physics and Experiments at Linear e^+e^- Colliders,’’ edited by P. M. Zerwas, Report No. DESY-93-123C.
[17] M. M. Nojiri, Phys. Rev. D **51**, 6281 (1995).
[18] F. Cuypers, G. Jan van Oldenborgh, and R. Rückl, Nucl. Phys. **B409**, 128 (1993).
[19] H.-C. Cheng, Report No. FERMILAB-CONF-97/418-T, hep-ph/9712427.