Rare decays of the top quark in the minimal supersymmetric model

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The decays $t\rightarrow cV$ ($V=\gamma,g$, or Z) induced through loop processes are calculated in the minimal supersymmetric model. We find that these new contributions can enhance the standard model branching fractions by as much as 3–4 orders of magnitude, i.e., $B(t\rightarrow cg)\sim 10^{-6}$, $B(t\rightarrow cZ)\sim 10^{-8}$, and $B(t\rightarrow c\gamma)\sim 10^{-8}$, for favorable values of the parameters.

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I. INTRODUCTION

Present experimental results [1] and the maximum-likelihood analysis [2] including full radiative corrections have constrained the mass of the top quark in the standard model (SM) to be in the range of 91 GeV $<m_t<$ 200 GeV at 95% C.L. One of the most important tasks at future e^+e^- and hadron colliders will be the careful investigation of the production and decay of top quarks. With future upgrades and increases in total integrated luminosity, experiments at the Fermilab Tevatron [3] should be able to explore the full range of m_t allowed by the SM. With the operation of CERN Large Hadron Collider (LHC) and Superconducting Super Collider (SSC), one expects to obtain roughly $10^7-10^8 t\bar{t}$ pairs per year [4] and thus may be able to observe various top interactions, which will allow further tests of the SM and provide fruitful information about new physics beyond the SM. One of the most characteristic predictions of the SM is the very small magnitude of flavor-changing neutral currents (FCNC's). The FCNC decays of top quark $t\rightarrow cV$ and $t\rightarrow cH$ have been calculated in the SM [5,6] and none of them is found to occur at detectable levels. So, detecting such FCNC top decays will be the excellent probes for the effects of new physics. In theories with additional Higgs doublets and additional symmetries, the magnitude of these decays may be significantly enhanced. Recently, several authors [6,7] evaluated the contributions of charged Higgs bosons to $t\rightarrow cV$ in the context of two Higgs doublet models (2HDM's) and found that such new contributions can enhance the SM branching fractions by as much as 3–4 orders of magnitude. In this paper we present the calculation of the supersymmetric QCD and chargino contributions to $t\rightarrow cV$ in the minimal supersymmetric standard model (MSSM) and compare these new contributions with the charged Higgs boson correction.

II. $t\rightarrow cV$ THROUGH SUPERSYMMETRIC QCD LOOP

Supersymmetric QCD violates flavor symmetry [8,9] and this can permit the rare decays $t\rightarrow cV$. The flavor changing strong interaction between gluinos ($\tilde{g}$), quarks (q) and squarks ($\tilde{q}$) can be found in Ref. [9]. The diagrams for the mode $t\rightarrow cV$ ($V=Z,\gamma,g$) through the supersymmetric QCD loop are shown in Fig. 1(a), where $\tilde{q}_\alpha$ (squark) is shorthand for a left-handed squark. The mass eigenstates of squarks are obtained by mixing the left- and right-handed squarks with the mixing angle θ [10]. Here we consider the unmixed case ($\theta=0$) in which the left-handed squark is a mass eigenstate. Since the top quark is quite heavy, the charm-quark mass is negligible. After a straightforward calculation, one obtains an effective tcV vertex of the form

$$V^\mu(tcZ)=-i\frac{e}{s_W c_W}\left[\frac{1}{2}-\frac{2}{3}s_W^2\right]\times(\gamma^\mu P_L F_1-ik_\nu\sigma^{\mu\nu}P_R F_2)\ , \tag{1}$$

$$V^\mu(tc\gamma)=-i\frac{2}{3}e(\gamma^\mu P_L F_1-ik_\nu\sigma^{\mu\nu}P_R F_2)\ , \tag{2}$$

$$V^\mu(tcg)=-ig_s T^a(\gamma^\mu P_L F_1-ik_\nu\sigma^{\mu\nu}P_R F_2)\ , \tag{3}$$

where $P_{R,L}=\frac{1}{2}(1\pm\gamma_5)$, $s_W=\sin\theta_W$, and $c_W=\cos\theta_W$. The form factors $F_{1,2}$ are given by

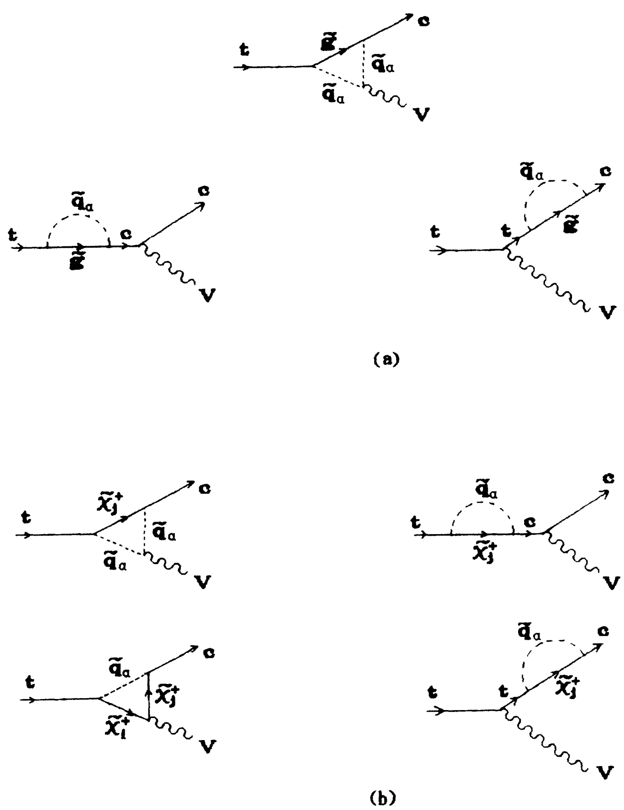

FIG. 1. Feynman diagrams: (a) induced by supersymmetric QCD, where $\tilde{g}$ stands for gluino and $\tilde{q}_\alpha$ stands for the left-handed up-type squarks of different flavors ($\tilde{q}_{2,3}=\tilde{c},\tilde{t}$); (b) induced by virtual charginos, where $\tilde{\chi}_j^+$ stand for charginos and $\tilde{q}_\alpha$ stand for down-type squarks of different flavors ($\tilde{q}_{2,3}=\tilde{s},\tilde{b}$).

$$F_1=\frac{\alpha_s C_F}{2\pi}\sum_{\alpha=2,3} V_{\alpha 2}V_{\alpha 3}[B_1+2c_{24} - m_t^2(c_{12}+c_{23}-c_{11}-c_{21})] \,, \tag{4}$$

$$F_2=\frac{\alpha_s C_F}{2\pi}\sum_{\alpha=2,3} V_{\alpha 2}V_{\alpha 3} m_t(c_{12}+c_{23}-c_{11}-c_{21}) \,, \tag{5}$$

where $B_1=B_1(m_t, m_{\tilde{g}}, \tilde{m}_\alpha)$ and $c_{ij}=c_{ij}(-p_t, k, m_{\tilde{g}}, \tilde{m}_\alpha, \tilde{m}_\alpha)$ are two- and three-point integrals whose definitions can be found in Ref. [11]. p_t and k are the momentum of the top and vector bosons, respectively. $m_{\tilde{g}}$ is the gluino mass and $\tilde{m}_\alpha$ is the top-squark mass for $\alpha=3$ and the scharm mass for $\alpha=2$. V_{ij} is the element of the unitary matrix V whose form is similar to the usual Kobayashi-Maskawa (KM) matrix and can be found in Ref. [9]. In our calculation we neglect the scalar u-quark ($\alpha=1$) contribution since it is highly suppressed by $V_{12}V_{13}$. The ultraviolet divergence is contained in $B_{0,1}$ and c_{24} via $B_0=\Delta-\bar{B}_0$, $B_1=-\Delta/2+\bar{B}_1$, and $c_{24}=\frac{1}{4}\Delta+\bar{c}_{24}$, where $\Delta=1/\epsilon-\gamma_E+\ln 4\pi$. It is easy to see that all the ultraviolet divergences have canceled in the effective vertex.

The partial widths for $t\to cV$ are then given by

$$\Gamma(t\to cZ)=\frac{\alpha}{8m_t^3 s_W^2 c_W^2}\left(\tfrac{1}{2}-\tfrac{2}{3}s_W^2\right)^2(m_t^2-m_Z^2)^2 \times\left[\frac{m_t^2}{m_Z^2}F_1^2+2F_1^2+6m_tF_1F_2 +(2m_t^2+m_Z^2)F_2^2\right] \,, \tag{6}$$

$$\Gamma(t\to c\gamma)=\frac{\alpha}{18}m_t(2F_1^2+6m_tF_1F_2+2m_t^2F_2^2) \,, \tag{7}$$

$$\Gamma(t\to cg)=\frac{\alpha_s}{2}m_t(2F_1^2+6m_tF_1F_2+2m_t^2F_2^2) \,. \tag{8}$$

In this paper the branching ratios $B(t\to cV)$ are defined as [6]

$$B(t\to cV)=\Gamma(t\to cV)/\Gamma(t\to W^+b) \,. \tag{9}$$

Note that if the charged Higgs boson is lighter than the top so that $t\to H^+b$ is kinematically allowed, the branching ratios are slightly smaller for some values of the parameter $\tan\beta$. Since $V_{23}=-V_{32}$ [9], we have to consider the mass splitting between the top squark and scharm; otherwise the contribution from top squark and scharm will cancel. In our numerical calculation we fix the relative squark mass splitting $r=10\%$ [9], i.e., $m_{\tilde{c}}=90\%\ m_{\tilde{t}}$ and we take $V_{23}^2=\epsilon^2=0.25$ [9]. Other input parameters are the same as Ref. [6], i.e., $m_Z=91.177$ GeV, $m_W=80.1$ GeV, $s_W^2=0.23$, $G_F=1.166\,372\times10^{-5}$ $(\mathrm{GeV})^{-2}$, $\alpha_{\mathrm{em}}=1/128.8$, $\alpha_s=1.4675/\ln(m_t^2/\Delta_{\mathrm{QCD}}^2)$ with $\Delta_{\mathrm{QCD}}=180$ MeV. The results are summarized in Figs. 2–5. Figures 2–4 show that supersymmetric (SUSY) QCD contributions to $B(t\to cV)$ depend strongly on the gluino and squark masses. For $m_{\tilde{g}}, m_{\tilde{t}}<120$ GeV, these new contributions can enhance the standard model branching fractions by as much as 3–4 orders of magnitude, i.e., $B(t\to cg)\sim10^{-6}$, $B(t\to cZ)\sim10^{-9}$, and $B(t\to c\gamma)\sim10^{-8}$. Figure 5 shows the dependence of supersymmetric QCD contributions to $B(t\to cV)$ on the value of top mass. Except for $B(t\to cZ)$, the results are

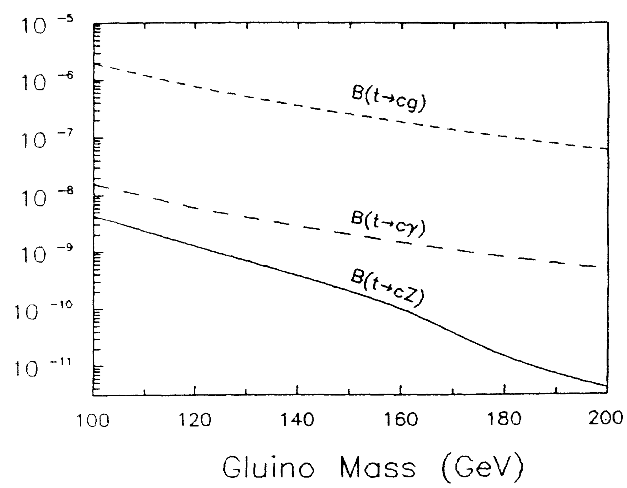

FIG. 2. Supersymmetric QCD contribution to $B(t\to cV)$ versus the gluino mass for $m_t=150$ GeV and $m_{\tilde{t}}=100$ GeV.

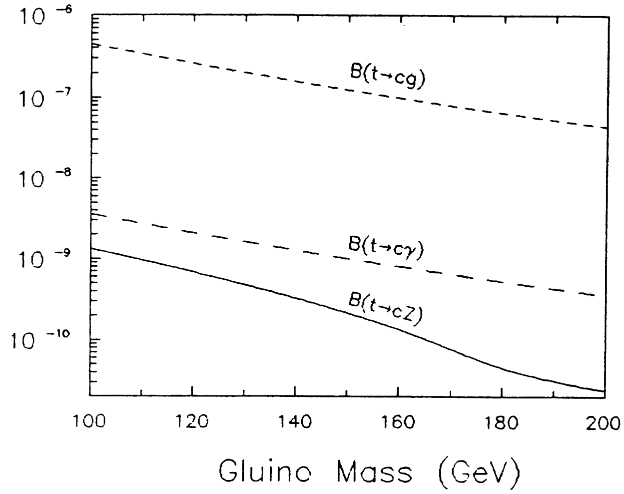

FIG. 3. The same as Fig. 2, but for $m_{\tilde{t}}=150$ GeV.

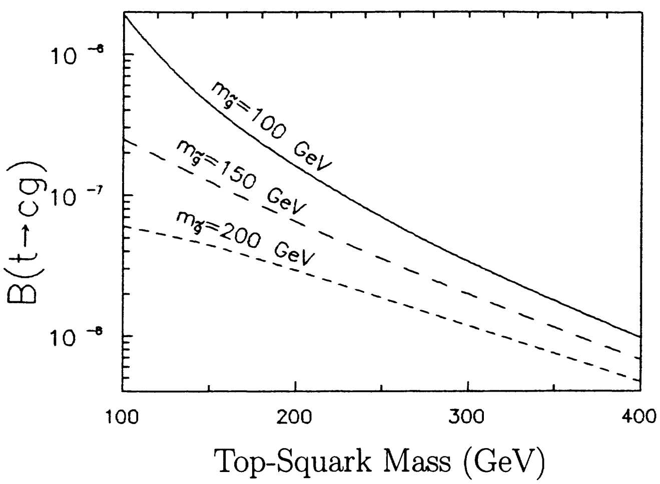

FIG. 4. Supersymmetric QCD contribution to $B(t\to cg)$ versus top-squark mass for $m_t=150$ GeV.

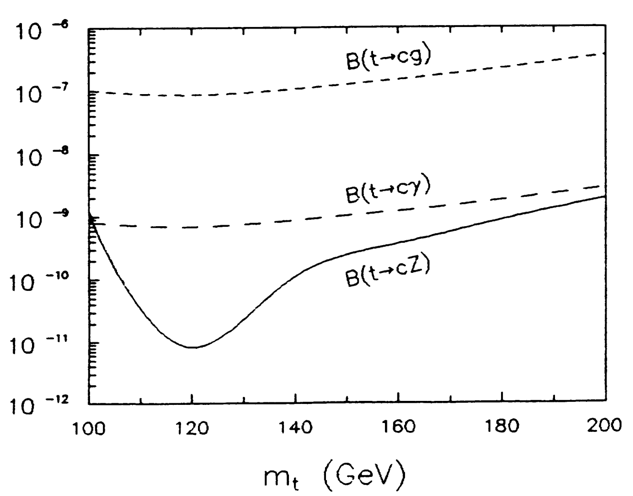

FIG. 5. Supersymmetric QCD contribution to $B(t\to cV)$ versus top mass for $m_{\tilde{t}}=m_{\tilde{g}}=150$ GeV.

not very sensitive to top mass.

As we see from Figs. 2–4, these contributions decrease rapidly as the masses of gluino and squark increase. The recent Collider Detector at Fermilab (CDF) limits [12] on the masses of squarks and gluinos are $m_{\tilde{g}}>150$ GeV (independently of $m_{\tilde{q}}$) and $m_{\tilde{q}}>150$ GeV (for $m_{\tilde{g}}<400$ GeV). However, the above CDF limits rely on some assumptions not supported by MSSM, one of which is that squarks and gluinos are supposed to decay directly to the lightest supersymmetric particle without intermediate decays to charginos or neutralinos [13]. An analysis [14] without such an assumption allows one to estimate that the CDF limits should be lowered by about 30 GeV. Moreover, analyzing the Tevatron dilepton data in terms of the R-parity-violating SUSY model yields a mass limit $m_{\tilde{g}}>100$ GeV, $m_{\tilde{q}}>100$ GeV [15]. So, if squarks and gluinos take their lowest allowed masses, the SUSY QCD contributions can greatly enhance the SM branching fractions for $t\to cV$.

III. $t\to cV$ THROUGH CHARGINO LOOP

The detailed discussion about the effect of generational mixing on $q\tilde{q}\tilde{\chi}^+$ and $q\tilde{q}\tilde{\chi}^0$ can be found in Ref. [16]. Here we consider *case* I of Ref. [16], in which the interaction $u_i\tilde{d}_j\tilde{\chi}^+$ with up-type quark u_i and down-type squark $\tilde{d}_j$ in different generations is suppressed by KM matrix while $q\tilde{q}\tilde{\chi}^0$ is exactly flavor diagonal. So, the rare decays $t\to cV$ can be induced through virtual charginos via interaction $u_i\tilde{d}_j\tilde{\chi}^+$. The corresponding diagrams are shown in Fig. 1(b). The relative Feynman rules can be found in Refs. [10,12]. Summing up these graphs results in an effective tcV vertex of the form

$$V^\mu(tcZ)=-i\gamma^\mu P_L F_{Z1}+k_\nu\sigma^{\mu\nu}P_R F_{Z2}\ , \tag{10a}$$

$$V^\mu(tc\gamma)=-i\gamma^\mu P_L F_{\gamma 1}+k_\nu\sigma^{\mu\nu}P_R F_{\gamma 2}\ , \tag{10b}$$

$$V^\mu(tcg)=-ig_s T^a(\gamma^\mu P_L F_{g1}+ik_\nu\sigma^{\mu\nu}P_R F_{g2})\ , \tag{10c}$$

where the form factors are given by

$$F_{Z1}=\frac{\alpha}{4\pi s_W^2}\frac{e}{s_W c_W}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}(F_{Z1}^a+F_{Z1}^b+F_{Z1}^c)\ , \tag{11}$$

$$F_{Z2}=\frac{\alpha}{4\pi s_W^2}\frac{e}{s_W c_W}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}(F_{Z2}^a+F_{Z2}^b)\ , \tag{12}$$

$$F_{\gamma 1}=\frac{\alpha}{4\pi s_W^2}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}(F_{\gamma 1}^a+F_{\gamma 1}^b+F_{\gamma 1}^c)\ , \tag{13}$$

$$F_{\gamma 2}=\frac{\alpha}{4\pi s_W^2}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}(F_{\gamma 2}^a+F_{\gamma 2}^b)\ , \tag{14}$$

$$F_{g1}=\frac{\alpha}{4\pi s_W^2}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}(F_{g1}^a+F_{g1}^c)\ , \tag{15}$$

$$F_{g2}=\frac{\alpha}{4\pi s_W^2}\sum_{\alpha=2,3}V_{2\alpha}^{\rm KM}V_{3\alpha}^{\rm KM}F_{g2}^a\ , \tag{16}$$

with

$$F_{Z1}^{a}=\left(\frac{1}{2}-\frac{1}{3}s_W^2\right)\sum_j[-m_t\lambda_t\tilde{M}_jU_{j1}V_{j2}(c_0+c_{11})+m_t^2U_{j1}^2(c_{12}+c_{23}-c_{11}-c_{21})-2U_{j1}^2c_{24}]\ , \tag{17}$$

$$F_{Z1}^{b}=\sum_{i,j}[O_{ij}^{\prime R}U_{i1}U_{j1}(\tfrac{1}{2}-2C_{24}-m_Z^2c_{12}-m_Z^2c_{23})+m_t\lambda_t\tilde{M}_iO_{ij}^{\prime L}U_{i1}V_{j2}(c_{11}-c_{12})]\ , \tag{18}$$

$$F_{Z1}^{c}=\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)\times\sum_j\left\{\frac{\lambda t}{m_t}\tilde{M}_jU_{j1}V_{j2}\times[B_0(m_t,\tilde{M}_j,\tilde{m}_\alpha)-B_0(0,\tilde{M}_j,\tilde{m}_\alpha)]+U_{j1}^2B_1(m_t,\tilde{M}_j,\tilde{m}_\alpha)\right\}\ , \tag{19}$$

$$F_{Z2}^{a}=\left(\frac{1}{2}-\frac{1}{3}s_W^2\right)\sum_j[-\lambda_t\tilde{M}_jU_{j1}V_{j2}(c_0+c_{11})+m_tU_{j1}^2(c_{12}+c_{23}-c_{11}-c_{21})]\ , \tag{20}$$

$$F_{Z2}^{b}=\sum_{i,j}[\lambda_t\tilde{M}_jO_{ij}^{\prime R}U_{i1}V_{j2}(c_0+c_{11})-\lambda_t\tilde{M}_iO_{ij}^{\prime L}U_{i1}V_{j2}c_{12}+m_tO_{ij}^{\prime R}U_{i1}U_{j1}(c_{11}+c_{21}-c_{12}-c_{23})]\ , \tag{21}$$

$$F_{\gamma1,2}^{a}=\frac{e}{3}F_{Z1,2}^{a}\Big/\left(\frac{1}{2}-\frac{1}{3}s_W^2\right)\ , \tag{22}$$

$$F_{\gamma1,2}^{b}=-eF_{Z1,2}^{b}|_{O_{ij}^{\prime L}\to1,O_{ij}^{\prime R}\to1,j\to i,m_Z\to0}\ , \tag{23}$$

$$F_{\gamma1}^{c}=\frac{2e}{3}F_{Z1}^{c}\Big/\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)\ , \tag{24}$$

$$F_{g1,2}^{a}=-F_{Z1,2}^{a}/(\tfrac{1}{2}-\tfrac{1}{3}s_W^2)\ , \tag{25}$$

$$F_{g1}^{c}=F_{Z1}^{c}/(\tfrac{1}{2}-\tfrac{2}{3}s_W^2)\ . \tag{26}$$

In the above $O_{ij}^{\prime L,R}$ is given in Eq. (c88) of Ref. [10], $\lambda_t=m_t/(\sqrt{2}m_W\sin\beta)$, and U_{ij} and V_{ij} are the elements of 2×2 matrices U and V which are given in Eq. (c19) of Ref. [10]. The chargino mass $\tilde{M}_j$ depend on the parameters M, μ, and $\tan\beta$, which is given in Eq. (c18) of Ref. [10]. Note that for $F_{Z1,2}^{a}$ in Eqs. (17) and (20),

$$c_0,c_{ij}=c_0,c_{ij}(-p_t,k,\tilde{M}_j,\tilde{m}_\alpha,\tilde{m}_\alpha)\ ,$$

while for $F_{Z1,2}^{b}$ in Eqs. (18) and (21),

$$c_0,c_{ij}=c_0,c_{ij}(-p_t,p_c,\tilde{M}_j,\tilde{m}_\alpha,\tilde{M}_i)\ .$$

Using the unitary property of the matrix U,V we found through simple calculation that all the ultraviolet divergences have canceled in the effective vertex, as they should.

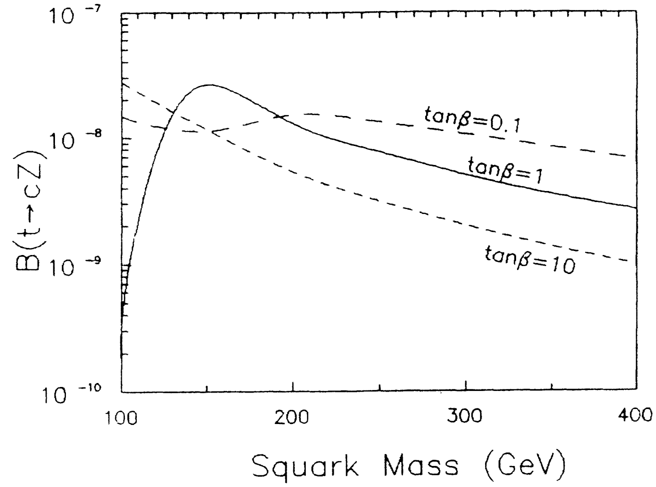

FIG. 6. The virtual chargino contribution to $B(t\to cZ)$ versus squark mass $m_{\tilde{q}}(m_{\tilde{q}}=m_{\tilde{b}}=m_{\tilde{s}})$ for $m_t=150$ GeV, $M=50$ GeV, and $\mu=30$ GeV.

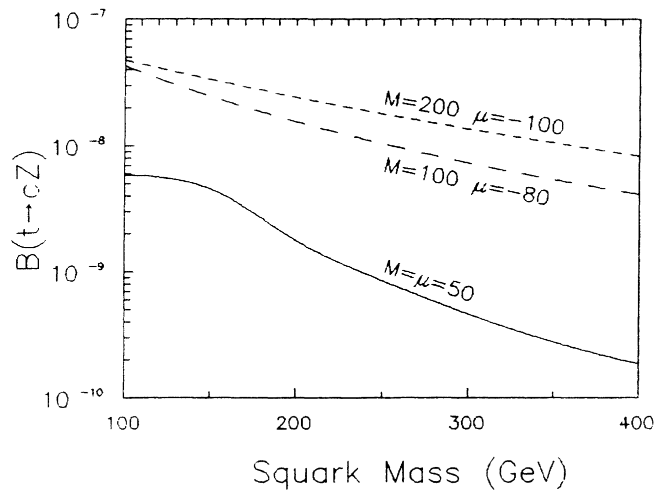

FIG. 7. The same as Fig. 6, except for $m_t=150$ GeV and $\tan\beta=1$.

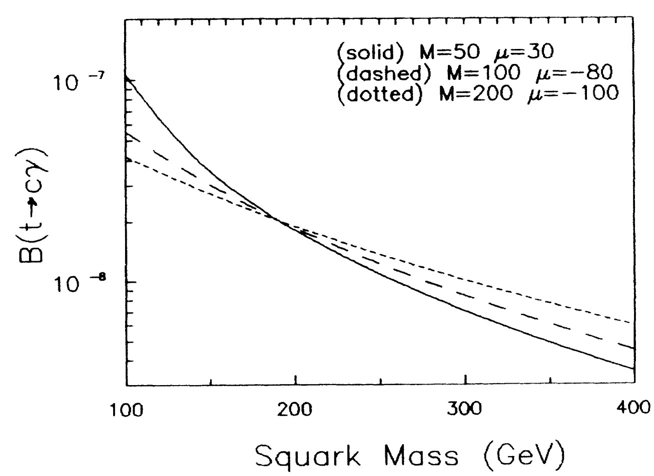

FIG. 8. The virtual chargino contribution to $B(t\to c\gamma)$ versus squark mass $m_{\tilde{q}}(m_{\tilde{q}}=m_{\tilde{b}}=m_{\tilde{s}})$ for $m_t=150$ GeV and $\tan\beta=1$.

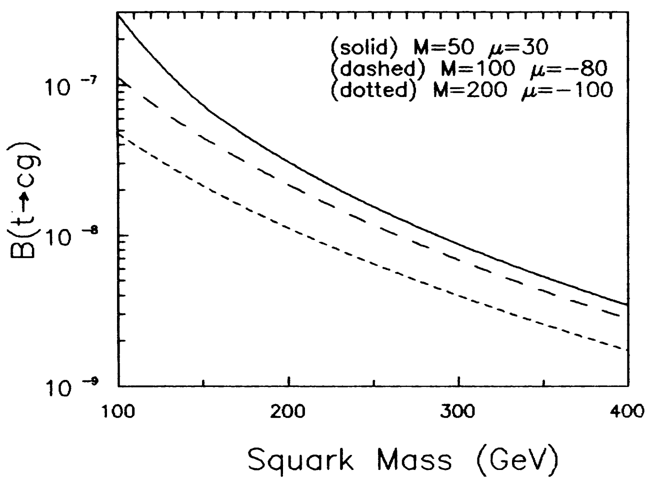

FIG. 9. The same as Fig. 8, except for $t \to cg$.

The virtual chargino contributions to the decay rate for $t \to cV$ are given by

$$\Gamma'(t \to cZ) = \frac{1}{32 m_t^3}(m_t^2 - m_Z^2)^2 \times \left[\frac{m_t^2}{m_Z^2} F_{Z1}^2 + 2F_{Z1}^2 - 6 m_t F_{Z1} F_{Z2} + (2m_t^2 + m_Z^2) F_{Z2}^2 \right] , \quad (27)$$

$$\Gamma'(t \to c\gamma) = \frac{m_t}{32\pi}(2F_{\gamma 1}^2 - 6 m_t F_{\gamma 1} F_{\gamma 2} + 2 m_t^2 F_{\gamma 2}^2) , \quad (28)$$

$$\Gamma'(t \to cg) = \frac{\alpha_s}{2} m_t (2F_{g1}^2 - 6 m_t F_{g1} F_{g2} + 2 m_t^2 F_{g2}^2) . \quad (29)$$

In our numerical calculations, we assume $m_{\tilde{b}} = m_{\tilde{s}}$ and take $V_{22}^{\mathrm{KM}} = 0.05$ [17]. Other input parameters are the same as in Sec. II. The parameters M, μ, and $\tan\beta$ can vary in a large range [18]. In Figs. 6–9 we plot the chargino contributions to $B(t \to cV)$ versus squark mass for different values of the parameters M, μ, and $\tan\beta$. Such contributions can significantly enhance the SM branching fractions for $t \to cV$, i.e., $\sim 10^{-7}$ for $B(t \to cg)$, $\sim 10^{-8}$ for $B(t \to cZ)$, and $B(t \to c\gamma)$ in the favorable case.

IV. DISCUSSION AND CONCLUSION

We have calculated and presented expressions for the FCNC top decays $t \to cV$ induced through supersymmetric QCD loop and chargino loop. We found the branching fractions for these decays to be enhanced significantly for some favorable values of the parameters. For comparison, we list the maximum levels of $B(t \to cV)$ predicted by the SM [6], by the 2HDM with charged Higgs-boson contributions [6], and by the MSSM with SUSY QCD and chargino contributions as follows:

	SM	2HDM	SUSY QCD	Charginos
$B(t \to cZ)$	10^{-12}	10^{-9}	10^{-9}	10^{-8}
$B(t \to c\gamma)$	10^{-12}	10^{-8}	10^{-8}	10^{-8}
$B(t \to cg)$	10^{-10}	10^{-6}	10^{-6}	10^{-7}

Note that charginos are the superpartners of charged Higgs bosons $H^\pm$ and $W^\pm$. In the chargino part we only considered the chargino corrections and did not calculate the contributions of $H^\pm$ and $W^\pm$ which have already been calculated in Ref. [6]. An old theorem [19] says the anomalous magnetic moment for a spin-$\frac{1}{2}$ fermion vanishes in the SUSY limit. Away from the SUSY limit the cancellations have somewhat less effect. So the different contributions of charginos, $H^\pm$ and $W^\pm$ to $t \to cV$ will cancel to some extent, and thus could make an order of magnitude difference in the chargino corrections. However, the SUSY QCD contributions are not affected. Thus the combined contributions of SUSY QCD and charginos are roughly 10^{-6} for $t \to cg$, 10^{-9} for $t \to cZ$ and 10^{-8} for $t \to (c\gamma)$ at the maximum level. Since the planned LHC and SSC can only produce roughly 10^7–$10^8 t\bar{t}$ pairs per year, $t \to cZ$ and $t \to c\gamma$ are certainly undetectable. The largest one, $t \to cg$, whose branching ratio is 10^{-6} in the favorable case, is also undetectable in SSC and LHC since it just gives two jets and there is no way to separate it from other jet backgrounds.

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