Top quark rare decay $t \to cH^i$ in the minimal supersymmetric model

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The top rare decays $t \to cH^i$ ($H^i = H, h, A$) induced by loop effects of the genuine supersymmetric particles are calculated in the minimal supersymmetric model. The analytic expressions are given for the partial width of these processes. The branching fraction of $t \to ch$ (h is the lightest Higgs boson) is found to be the largest one, the maximum level of which is $B(t \to ch) \sim 10^{-5}$.

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I. INTRODUCTION

The pursuit of the top quark and Higgs bosons predicted by the standard model (SM) and by the minimal supersymmetric model (MSSM) is one of the primary goals of the present and next generation of colliders. The SM top quark, with a mass [1,2] of 91 GeV $< m_t <$ 200 GeV, is expected to be discovered at the Fermilab Tevatron [3]. With the operation of the 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 might 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 the top quarks $t \to cV$ and $t \to cH$ have been calculated in the SM [5,6], and none of them is found to occur at detectable levels. Detecting such FCNC top decays will be an excellent probe for the effects of new physics. Recently, several authors [6,7] calculated top rare decays $t \to cV$ in the context of two Higgs doublet models (2HDM's) and the MSSM, and found that such new contributions can enhance the SM branching fractions by as much as 3–4 orders of magnitude. On the other hand, since the SM branching ratio of $t \to cH$ is unobservably small, if this decay mode is detected at future colliders, it would be an unmistakable signal for new physics, such as the 2HDM and MSSM. Here we focus on the MSSM, which is of phenomenological interest. In the MSSM [8], there are three neutral and two charged Higgs bosons, $H, h, A, H^{\pm}$ (H and h are CP even and A is CP odd), the masses and couplings of which are controlled by two parameters, i.e., m_A and $\tan\beta$, at the tree level. The mass upper bound [9] for the lightest CP-even Higgs boson h is $m_h < m_Z$ at the tree level and $m_h < m_Z + \epsilon(m_t, \tilde{m})$ when including radiative corrections [$\tilde{m}$ is the supersymmetric (SUSY) mass scale]. Thus $t \to ch$ is kinematically allowed in the whole parameter space. In the MSSM, the FCNC top decay can be induced by loop effects. In this paper, in the context of the MSSM, we calculate the FCNC top decay $t \to cH^i$ ($H^i = H, h, A$) induced by loop effects of the genuine SUSY particles and compare their branching fractions with the SM top decay $t \to cH$. Note that in this paper we only consider the loop effects of the genuine SUSY particles, not including the virtual W^+ and H^+ contributions, which appear in all the two Higgs doublet models.

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II. CALCULATIONS

A. SUSY QCD contribution

Supersymmetric QCD violates flavor symmetry [10] and thus can permit the rare decays $t \to cH^i$. The flavor-changing strong interaction between a gluino ($\tilde{g}$), quark (q), and squark ($\tilde{q}$) can be found in Ref. [10], in which the interaction is suppressed by a small element $V'_{\alpha\beta}$ of the unitary matrix V' for left-handed squarks while being exactly flavor diagonal for right-handed squarks. The Feynman diagrams for $t \to cH^i$ ($H^i = H, h, A$) through SUSY QCD loop are shown in Fig. 1(a), where $\tilde{u}_\alpha$ is shorthand for left-handed up-type squarks. The mass eigenstates of squarks are obtained by mixing the left- and right-handed squarks with the mixing angle θ_q [8]. In this paper we consider the mixing of left- and right-handed top squarks with a mixing angle $\theta_t = \theta$, but for other flavor squarks we consider the unmixed case

($\theta_q=0$) in which the left- and right-handed squarks are the mass eigenstates. Also, we take all squark masses to be degenerate ($\tilde{m}_c=\tilde{m}_s=\tilde{m}_b$) but the top squarks. The relative mass splitting between top squark and other squarks is denoted by $r=1-\tilde{m}_c/\tilde{m}_t$, which is retained as a free parameter in our numerical calculations. Note that we assume the two mass eigenstates of each squark have the same mass.

After a straightforward calculation one obtains an effective vertex

$$V_{\rm ren}=P_R F_R+P_L F_L \tag{1}$$

for $t\to cH$ and $t\to ch$ and

$$V_{\rm ren}=P_R F_R-P_L F_L \tag{2}$$

for $t\to cA$. Here $P_{R,L}=\frac{1}{2}(1\pm\gamma_5)$ and the form factors $F_{R,L}$ are given by

$$F_R=i\frac{\alpha_s C_F}{2\pi}\frac{e}{s_w}V'_{\alpha 2}V'_{\alpha 3}\left\{\frac{m_c^2 m_t}{m_t^2-m_c^2}\eta_{H^i}[B_1(m_c,\tilde{m}_g,\tilde{m}_\alpha)-B_1(m_t,\tilde{m}_g,\tilde{m}_\alpha)]+[\delta_{\alpha 2}+(1-\sin 2\theta)\delta_{\alpha 3}]\xi_{H^i}m_t(C_{12}-c_{11})\right\}, \tag{3}$$

$$F_L=i\frac{\alpha_s C_F}{2\pi}\frac{e}{s_w}V'_{\alpha 2}V'_{\alpha 3}\left\{\frac{m_t^2 m_c}{m_t^2-m_c^2}\eta_{H^i}[B_1(m_c,\tilde{m}_g,\tilde{m}_\alpha)-B_1(m_t,\tilde{m}_g,\tilde{m}_\alpha)]-[\delta_{\alpha 2}+(1-\sin 2\theta)\delta_{\alpha 3}]\xi_{H^i}m_c C_{12}\right\}, \tag{4}$$

with η_{H^i} and ξ_{H^i} given by

$$\begin{bmatrix}\eta_H & \xi_H\\ \eta_h & \xi_h\\ \eta_A & \xi_A\end{bmatrix}=\begin{bmatrix}\dfrac{\sin\alpha}{2m_W\sin\beta} & \dfrac{m_Z}{c_W}v_u\cos(\alpha+\beta)+\dfrac{m_\alpha^2\sin\alpha}{m_W\sin\beta}\\ \dfrac{\cos\alpha}{2m_W\sin\beta} & -\dfrac{m_Z}{c_W}v_u\sin(\alpha+\beta)+\dfrac{m_\alpha^2\cos\alpha}{m_W\sin\beta}\\ -i\dfrac{\cos\beta}{2m_W\sin\beta} & 0\end{bmatrix}. \tag{5}$$

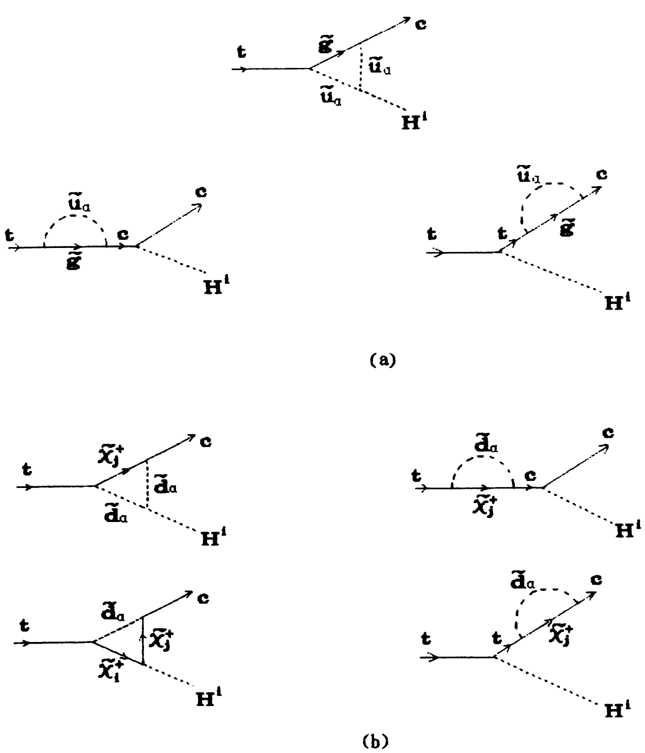

FIG. 1. Feynman diagrams for $t\to cH^i$ ($H^i=H,h,A$): (a) induced by supersymmetric QCD, where $\tilde{g}$ stands for gluino and $\tilde{u}_\alpha$ stands for the left-handed up-type squarks of different flavors ($\tilde{u}_{2,3}=\tilde{c},\tilde{t}$); (b) induced by virtual charginos, where $\tilde{\chi}_j^+$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

In the above, $v_u=\frac{1}{2}-e_u s_W^2$ ($e_u=\frac{2}{3}$), $s_W=\sin\theta_W$, $c_W=\cos\theta_W$, and $C_F=\frac{4}{3}$. The sum over α ($=2,3$) is implied in Eqs. (3) and (4). $\tilde{m}_g$ is the gluino mass, and $\tilde{m}_\alpha$ (m_α) is the top squark (top quark) mass for $\alpha=3$ and the scharm (charm) mass for $\alpha=2$. The functions B_1 and $C_{ij}=C_{ij}(-p_t,p_{H^i},\tilde{m}_g,\tilde{m}_\alpha,\tilde{m}_\alpha)$ are two- and three-point integrals whose definition can be found in Ref. [11]. $V'_{\alpha\beta}$ 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. [10]. In our calculation we have neglected 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 find that all the ultraviolet divergences have canceled in the effective vertex.

The SUSY QCD contributions to the decay rates of $t\to cH^i$ are then given by

$$\Gamma'(t\to cH^i)=\frac{1}{32\pi m_t^3}(m_t^2-m_{H^i}^2)^2[|F_L|^2+|F_R|^2]. \tag{6}$$

B. Chargino loop contribution

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. [12]. Here we only consider case I of Ref. [12], in which the interaction $u_i\tilde{d}_j\tilde{\chi}^+$ with an up-type quark u_i and down-type squark $\tilde{d}^j$ in different generations is suppressed by the small KM matrix elements while $q\tilde{q}\tilde{\chi}^0$ is exactly flavor diagonal. So the rare decays $t \to cH^i$ 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 and neglecting the masses of c, b, and s quarks, we get the effective vertex of the form

$$V_{\rm ren} = P_R(F_1 + F_2 + F_3) , \tag{7}$$

with

$$F_1 = i\frac{\alpha}{4\pi s_W^2}\frac{e}{s_W}\eta_{H^i}V_{\alpha 2}^{\rm KM}V_{\alpha 3}^{\rm KM}\lambda_t \tilde{M}_j U_{j1}V_{j2}B_0(m_c,\tilde{M}_j,\tilde{m}_\alpha) , \tag{8}$$

$$F_2 = i\frac{\alpha}{4\pi s_W^2}\frac{e}{s_W}\phi_{H^i}V_{\alpha 2}^{\rm KM}V_{\alpha 3}^{\rm KM}[\lambda_t \tilde{M}_j U_{j1}V_{j2}C_0 + m_t U_{j1}^2(C_{11}-C_{12})] , \tag{9}$$

$$\begin{aligned} F_3 = i\frac{\alpha}{4\pi s_W^2}\frac{e}{s_W}V_{\alpha 2}^{\rm KM}V_{\alpha 3}^{\rm KM}\{ &-\tilde{M}_j U_{i1}(\lambda_t \tilde{M}_i M_{ij}^{H^i}V_{j2} + m_t M_{ji}^{*H^i}U_{j1}^*)C_0 - m_t U_{i1}U_{j1}^* C_{11}(\tilde{M}_j M_{ji}^{*H^i} + \tilde{M}_i M_{ij}^{H^i}) \\ &+ \lambda_t M_{ji}^{*H^i}U_{i1}V_{j2}[m_t^2(C_{12}+C_{23}-C_{11}-C_{21}) - m_{H^i}^2(C_{12}+C_{23}) - 4C_{24} + \tfrac{1}{2}]\} , \end{aligned} \tag{10}$$

where $\lambda_t = m_t/(\sqrt{2}m_W \sin\beta)$, $v_d = -\frac{1}{2} - e_d s_W^2$ $(e_d = -\frac{1}{3})$, η_{H^i} is given in Eq. (5), and $\phi_{H^i}, M_{ij}^{H^i}$ are given by

$$\begin{pmatrix} \phi_H & M_{ij}^H \\ \phi_h & M_{ij}^h \\ \phi_A & M_{ij}^A \end{pmatrix} = \begin{pmatrix} -\frac{m_Z}{c_W}v_d\cos(\alpha+\beta) & Q_{ij}\cos\alpha + S_{ij}\sin\alpha \\ \frac{m_Z}{c_W}v_d\sin(\alpha+\beta) & -Q_{ij}\sin\alpha + S_{ij}\cos\alpha \\ 0 & i(Q_{ij}\sin\beta + S_{ij}\cos\beta) \end{pmatrix} , \tag{11}$$

with

$$Q_{ij} = \frac{1}{\sqrt{2}}V_{i1}U_{j2}, \quad S_{ij} = \frac{1}{\sqrt{2}}V_{i2}U_{j1} . \tag{12}$$

The sum over i,j $(=1,2)$ and α $(=2,3)$ is implied in Eqs. (8)–(10), where $\alpha=2,3$ for scalar s and b quarks, respectively. U_{ij} and V_{ij} are the elements of 2×2 matrices U and V which are given in Eq. (C19) of Ref. [8]. The chargino masses $\tilde{M}_j$ depend on the model parameters M, μ, and $\tan\beta$, which are given in Eq. (C18) of Ref. [8]. Note that, for F_2 in Eq. (9),

$$C_0, C_{ij} = C_0, C_{ij}(-p_t, p_{H^i}, \tilde{M}_j, \tilde{m}_\alpha, \tilde{m}_\alpha) ,$$

while, for F_3 in Eq. (10),

$$C_0, C_{ij} = C_0, C_{ij}(-p_t, p_c, \tilde{M}_j, \tilde{m}_\alpha, \tilde{M}_i) .$$

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

The virtual chargino contributions to the decay rate for $t \to cH^i$ are given by

$$\Gamma''(t \to cH^i) = \frac{1}{32\pi m_t^3}(m_t^2 - m_{H^i}^2)^2 |F_1 + F_2 + F_3|^2 . \tag{13}$$

Combining the contributions of supersymmetric QCD and chargino loops to the widths we obtain

$$\Gamma(t \to cH^i) = \Gamma'(t \to cH^i)\big|_{|F_R|^2 \to |F_R|^2 + |F_1+F_2+F_3|^2} \tag{14}$$

The branching ratios $B(t \to cV)$ are defined as [6]

$$B(t \to cH^i) = \Gamma(t \to cH^i)/\Gamma(t \to W^+ b) . \tag{15}$$

Note that if the charged Higgs boson is lighter than the top-quark and thus $t \to H^+ b$ is kinematically allowed, the branching ratios will be slightly smaller.

III. NUMERICAL RESULTS AND CONCLUSION

Before numerical calculation we need to specify the parameters involved. In the SUSY QCD part we take $V_{23}'^2 = \epsilon^2 = 0.25$ [10] and consider the relative squark mass splitting $r = 1 - \tilde{m}_c/\tilde{m}_t$ and the mixing angle θ between left- and right-handed top squarks as two free parameters. For the chargino part, we assume $\tilde{m}_b = \tilde{m}_s$ and take $V_{23}^{\rm KM} = 0.05$ [13]. The parameters M, μ can vary in a large range [14], which are fixed to be $M = 200$ GeV, $\mu = -100$ GeV in our numerical calculation. And we use the tree level relations [9] between the Higgs boson masses $m_{H,h,A}$ and parameters α, β, and choose $m_A, \tan\beta$ as two independent input parameters. Other input parameters are the same as Ref. [6], i.e., $m_Z = 91.177$ GeV, $m_W = 80.1$ GeV, $s_W^2 = 0.23$, $G_F = 1.166\,372 \times 10^{-5}$ $({\rm GeV})^{-2}$, $\alpha_{\rm em} = 1/128.8$, and $\alpha_s = 1.4675/\ln(m_t^2/\Lambda_{\rm QCD}^2)$, with $\Lambda_{\rm QCD} = 180$ MeV.

We present some numerical results in Figs. 2–7 with $m_t = 150$ GeV. Figures 2 and 3 show that SUSY QCD contributions to $B(t \to cH^i)$ depend strongly on the gluino and squark masses, decreasing rapidly as the masses of gluino and squark increase. From Fig. 5 we see that the chargino contributions also decrease as squark mass increases. The recent Collider Detector at Fermilab (CDF) limits [15] on the masses of squarks and gluinos

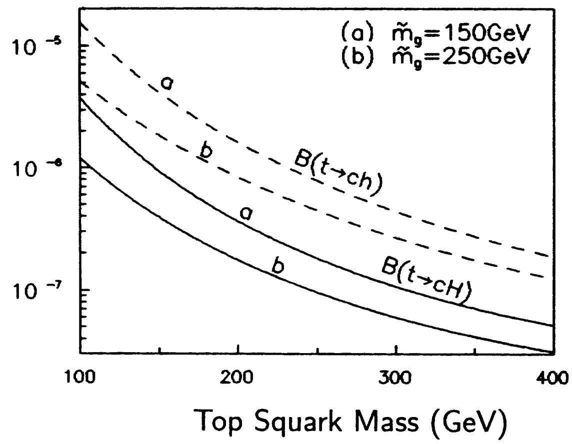

FIG. 2. Supersymmetric QCD contribution to the branching fractions versus top squark mass with $m_A = 100$ GeV, $\tan\beta = 5$, $\theta = 0$, and $r = 0.1$ for $t \to cH$ and $t \to ch$.

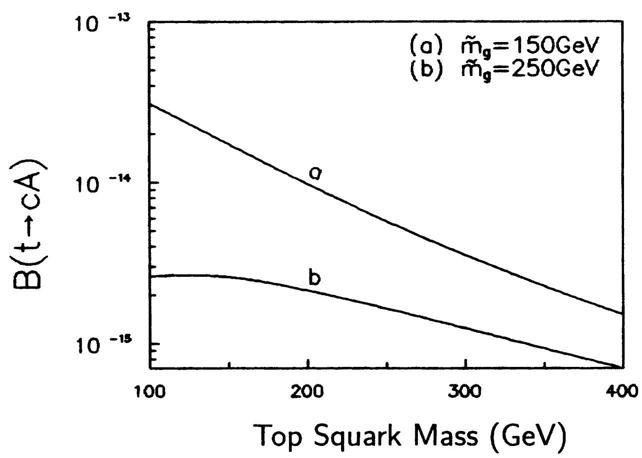

FIG. 3. Same as Fig. 2, but for $t \to cA$.

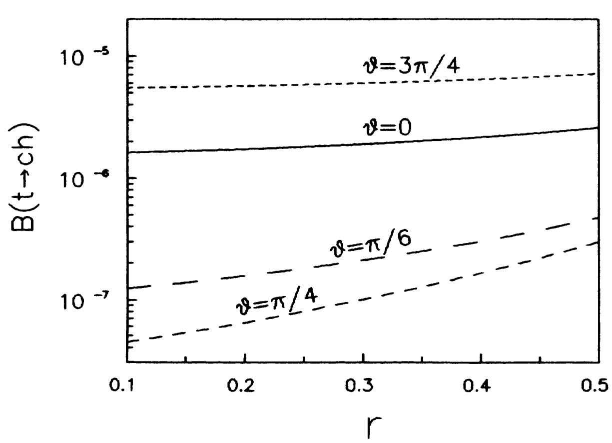

FIG. 4. Supersymmetric QCD contribution to $B(t \to ch)$ vs $r = 1 - \tilde{m}_c / \tilde{m}_t$ with different values of θ and $m_A = 100$ GeV, $\tan\beta = 5$, $\tilde{m}_t = 200$ GeV, and $\tilde{m}_g = 150$ GeV.

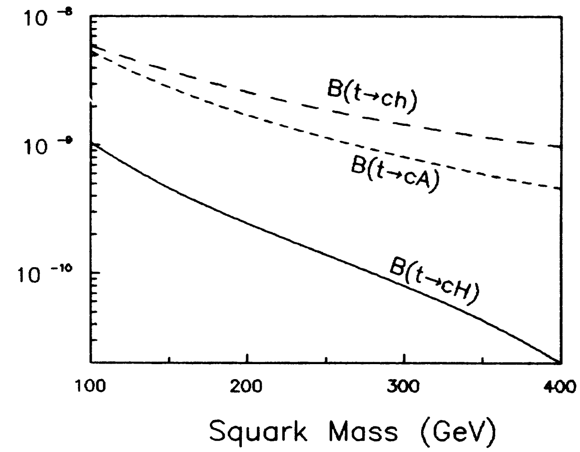

FIG. 5. Virtual chargino contribution to the branching fractions vs squark mass ($\tilde{m}_q = \tilde{m}_b = \tilde{m}_s$) for $m_A = 100$ GeV and $\tan\beta = 5$.

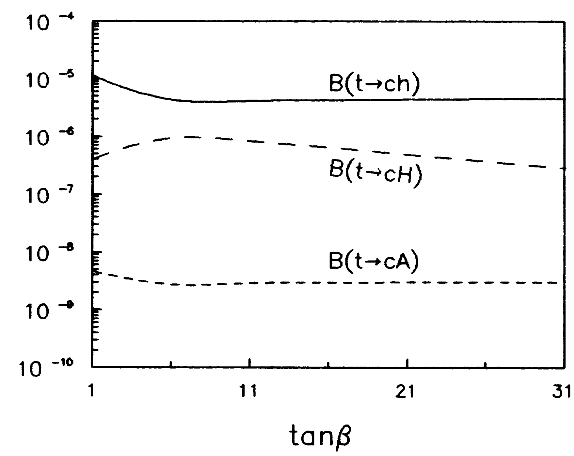

FIG. 6. Combined contribution of supersymmetric QCD and virtual charginos to $B(t \to cH^i)$ vs $\tan\beta$ with $m_A = 100$ GeV, $\tilde{m}_g = \tilde{m}_c = \tilde{m}_b = \tilde{m}_s = 150$ GeV, $\theta = 0$, and $r = 0.1$.

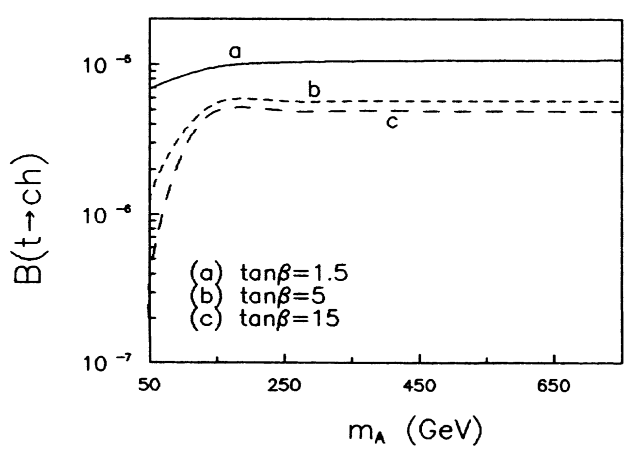

FIG. 7. Combined contribution of supersymmetric QCD and virtual charginos to $B(t \to ch)$ vs m_A with $\tilde{m}_g = \tilde{m}_c = \tilde{m}_b = \tilde{m}_s = 150$ GeV, $\theta = 0$, and $r = 0.1$.

are $\tilde{m}_g > 150$ GeV (independently of $\tilde{m}_q$) and $\tilde{m}_q > 150$ GeV (for $\tilde{m}_g < 400$ GeV), which rely on some assumptions not supported by the MSSM [16]. A more general analysis [17] allows one to estimate that the collider detector at Fermilab (CDF) limits should be lowered by about 30 GeV. Figure 4 shows the dependence of the SUSY QCD contribution to $B(t \rightarrow ch)$ on r and θ. In Figs. 6 and 7 we present the combined contribution of supersymmetric QCD and chargino loop versus the parameters $\tan\beta$ and m_A, respectively. The largest branching fraction is $B(t \rightarrow ch)$. For all the parameter space of m_A and $\tan\beta$, $t \rightarrow ch$ is kinematically allowed, and as shown in Fig. 7, its branching fraction can reach $\sim 10^{-6}-10^{-5}$. On the contrary, $t \rightarrow cH$ and $t \rightarrow cA$ can only occur in a small part of parameter space, and as shown in Fig. 6, their branching fractions are much smaller than $B(t \rightarrow ch)$.

Since the SM decay $t \rightarrow cH$ has a branching ratio of $\sim 10^{-7}$ [6], which is certainly undetectable at SSC or LHC, detecting this decay mode would be a breakthrough into the new physics world. The planned SSC and LHC will produce roughly 10^8 $t\bar{t}$ pairs per year, but the tagging by a semileptonic decay reduces that by an order of magnitude. And what is left is a decay of a top quark into three jets, which looks very much like the decays of a top quark into W^+b. So the MSSM decay $t \rightarrow ch$ ($h \rightarrow b\bar{b}$) at its maximum level $\sim 10^{-5}$ also seems to be undetectable at SSC or LHC. As is pointed by Kane [4], a high-energy linear e^+e^- collider [the Next Linear Collider (NLC)] with 400 GeV $< \sqrt{s} <$ 500 GeV and $L > 3 \times 10^{32}$ cm^{-2} sec^{-1} is a very powerful device for top quark physics and could be the ideal place to study top quark rare decays. At NLC, rare decays of the top quark could be searched for down to a very small branching ratio, and a systematic and general search for top rare decay modes may be possible. However, even at NLC, our results for $t \rightarrow ch$ might not correspond to a detectable level. Detailed background studies are needed for a definite conclusion.

In conclusion, we have calculated top rare decays $t \rightarrow cH^i$ ($H^i = H, h, A$) induced by loop effects of the genuine SUSY particles in the MSSM. Our results show that branching fraction of $t \rightarrow ch$ (h is the lightest Higgs boson) can be up to $\sim 10^{-5}$ for favorable parameter values, which is much larger than the SM result $B(t \rightarrow cH) \sim 10^{-7}$.

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